DEPARTMENT OF THE NAVY
NAVAL SURFACE WARFARE CENTER
CARDEROCK DIVISION

CARDEROCK DIVISION HEADQUARTERS
DAVID TAYLOR MODEL BASIN
9500 MACARTHUR BOULEVARD
WEST BETHESDA, MD 20817-5700

IN REPLY REFER TO:
5605
Ser 8500/2014004
31 Jan 2014

From: Commander, Naval Surface Warfare Center, Carderock Division
To: Commander, Naval Sea Systems Command (PMS385)

Subj: FORWARDING OF REPORT

Encl: (1) NSWCCD-80-TR-2013/015, "High Speed Trimaran (HST) Seatrain Experiments, Model 5714" by Eric Giesberg and Bryson Metcalf, December 2013
(2) Customer Project Survey Form 5000-20A (Rev 5)

1. Enclosure (1) is forwarded for your information and retention.

2. It is requested that enclosure (2) be completed and returned to the Carderock Division, Naval Surface Warfare Center. Customer surveys are conducted at the completion of a project and are used at the Department level to control and verify the system processes and capability. Your comments will be reviewed and are appreciated.

JUDE F. BROWN
By direction

Copy to:
NAVSEA PMS 385, S. Clark
SEA 05, J. Webster
P. Alman
SEA 05D1, J. Slutsky
CSC
DTIC

**DOCUMENT RECEIPT**

Date: 31 January 2014

| TO: | FROM: |
| --- | --- |
| DTIC<br>8725 John J Kingman Rd Suite 0944<br>Ft. Belvoir VA 22060-6218 | **Naval Surface Warfare Center, Carderock Division,**<br>**9500 MacArthur Blvd**<br>**Code** 8500<br>**West Bethesda, MD 20817-5700** |

The following material is transmitted for official use:

NSWCCD-80-TR-2013/015 "High Speed Trimaran (HST) Seatrain Experiments, Model 5714" by Eric Giesberg and Bryson Metcalf, December 2013
Approved for Public Release. Distribution Unlimited

Please sign and return

Date of Receipt________________ Signature and Title____________________________

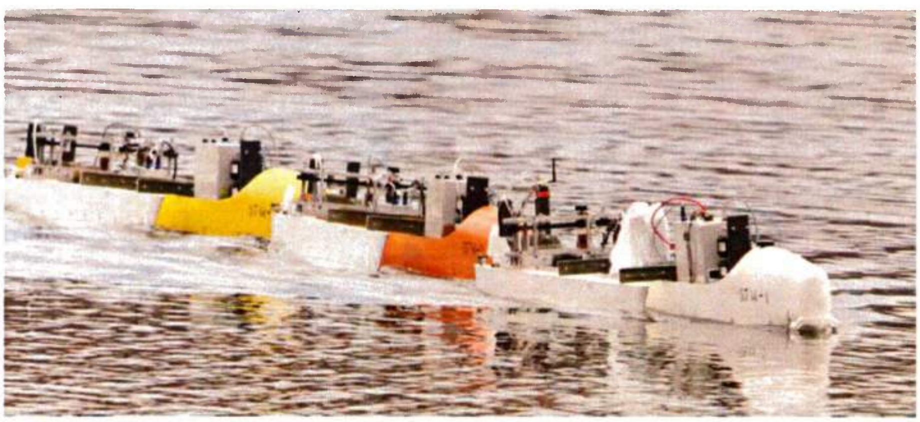
Form 5000-9G (Rev 3) FEBRUARY 2002

Naval Surface Warfare Center
Carderock Division
West Bethesda, Maryland 20817-5700

NSWCCD-80-TR-2013/015 December 2013
Naval Architecture and Engineering Department Report

# High Speed Trimaran (HST) Seatrain Experiments, Model 5714

By
Eric Giesberg
Bryson Metcalf



Approved for Public Release. Distribution Unlimited.

NSWCCD-80-TR-2013/015 High Speed Trimaran (HST) Seatrain Experiments, Model 5714

# REPORT DOCUMENTATION PAGE

*Form Approved*
*OMB No. 0704–0188*



**1. REPORT DATE** *(DD-MM-YYYY)*
01-12-2013

**2. REPORT TYPE**
Draft

**3. DATES COVERED** *(From - To)*
Aug. 2011 - Oct. 2011

**4. TITLE AND SUBTITLE**
High Speed Trimaran (HST) Seatrain Experiments, Model 5714

**5a. CONTRACT NUMBER**
N0002410WX21084

**5b. GRANT NUMBER**

**5c. PROGRAM ELEMENT NUMBER**
0408042N

**6. AUTHOR(S)**
Eric Giesberg
Bryson Metcalf

**5d. PROJECT NUMBER**
3116

**5e. TASK NUMBER**

**5f. WORK UNIT NUMBER**
10-1-2125-148-85

**7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)**
Naval Surface Warfare Center
Carderock Division
9500 MacArthur Boulevard
West Bethesda, MD 20817-5700

**8. PERFORMING ORGANIZATION REPORT NUMBER**
NSWCCD-80-TR-2013/015

**9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)**
Naval Sea Systems Command PMS 385
1333 Isaac Hull Avenue S.E., STOP # 2501
Washington Navy Yard, D.C. 20376-2501

**10. SPONSOR/MONITOR'S ACRONYM(S)**
NAVSEA PMS 385

**11. SPONSOR/MONITOR'S REPORT NUMBER(S)**

**12. DISTRIBUTION/AVAILABILITY STATEMENT**
Approved for Public Release. Distribution Unlimited.

20140206049

**13. SUPPLEMENTARY NOTES**

**14. ABSTRACT**
A model of a high speed trimaran seatrain concept was tested for resistance, statics, and controllability. The seatrain, of identical trimaran units developed from the original NSWC Carderock Division connector-less concept, was proposed by CSC as a solution for the America's Marine Highway initiative. Four identical 10 foot long self propelled models were built for the purpose of measuring resistance of incrementally increasing in length seatrains. A series of towed and self-propelled model tests were used for characterizing the effect of the seatrain on propeller inflow velocities. Hull forces and moments developed at varying yaw angles were measured for validating maneuvering simulations produced by CSC. The models were then remotely controlled to demonstrate the operational capabilities of the yaw articulating seatrain. The design showed resistance reductions of up to 30% in comparison to a single unit in resistance while having minimal effect on the inferred propeller inflow velocities. The forces and moments were successfully measured and recorded for simulation verification purposes. A sea train of two and three units successfully demonstrated that a seatrain can be controlled and maneuvered through a number of typical ship operations. It was found however that simple controllability will require development of an interdependent autopilot system.

**15. SUBJECT TERMS**
seatrain, HST, 5714

| 16. SECURITY CLASSIFICATION OF: a. REPORT | b. ABSTRACT | c. THIS PAGE | 17. LIMITATION OF ABSTRACT | 18. NUMBER OF PAGES | 19a. NAME OF RESPONSIBLE PERSON |
|---|---|---|---|---|---|
| | | | | 159 | **19b. TELEPHONE NUMBER** *(Include area code)* |

**Standard Form 298 (Rev. 8/98)**
Prescribed by ANSI Std. Z39.18

This page intentionally left blank.

# CONTENTS

# LIST OF FIGURES

# LIST OF TABLES

# NOMENCLATURE

| | | | |
|---|---|---|---|
| $V$ | Speed | | |
| $\Delta$ | Displacement | $R_n$ | Reynolds Number |
| $F_n$ | Froude Number | $R_T$ | Total Resistance |
| $C_T$ | Total Resistance Coefficient | $C_R$ | Residuary Resistance Coefficient |
| $C_F$ | Frictional Resistance Coefficient | $\lambda$ | Model Scale Ratio |
| $S$ | Wetted Surface Area | $\rho$ | Water Density |
| $\nu$ | Water Kinematic Viscosity | $LOA$ | Length Overall |
| $LWL$ | Length Waterline | $LBP$ | Length Between Perpendiculars |
| $ABL$ | Above Baseline | $FA$ | Full Appended Hull |
| $FP$ | Forward Perpendicular | $\nabla$ | Volume |
| $EHP$ | Effective Horsepower | $SHP$ | Ship Horsepower |
| $TF$ | Transport Factor | $RPM$ | Rotations Per Minute |
| $\eta_D$ | Propulsive Coefficient | | |
| DAQ | Data Acquisition | | |
| HST | High Speed Trimaran | | |
| NAVSEA | Naval Sea Systems Command | | |
| NSWCCD | Naval Surface Warfare Center Carderock Division | | |
| CSC | Computer Sciences Corp | | |
| AMTI | Advanced Mechanical Technology, Inc. | | |
| NI | National Instruments | | |
| PMS | Program Manager Ship | | |

This page intentionally left blank.

# ADMINISTRATIVE INFORMATION

The test results presented in this report were performed by the Hullform and Propulsor Testing Branch (Code 8540) within the Naval Architecture and Engineering Department of the Naval Surface Warfare Center, Carderock Division (NSWCCD) at the David Taylor Model Basin, herein referred to as DTMB. The work was sponsored by the Naval Sea Systems Command (NAVSEA) PMS 385 Strategic Sealift R&D Program.

# ACKNOWLEDGMENTS

The experimental work conducted herein was a combined effort from many members of the NSWCCD Naval Architecture and Engeering Department Code 80. The following people contributed to the success of this test program; Mr. Gabor Karafiath, Code 8500 for project management, Mr. David Schwarzenberg for model design and for leading the hull model construction efforts, Mr. Josh Crum, Mr. Dung Su, and Mr. Francisco Rodriguez all from code 3613 for model propeller manufacture, Mr. Donnie Walker Code 854 and Mr. Dennis Mullinix under contract for instrumentation support, Mr. Nathan Madzivanyika Code 854 for preliminary analysis and model testing support, Mr. Andrew Nowakowski Code 854 and Mr. Jesse Cruze Code 863, for model testing support. Mr. David Liese, lead from PMS 385, for support of investigation of seatrain concepts for Navy high speed and long distance ocean transport. Mr Igor Mizine from CSC was the lead naval architect for the design of the Seatrain Trimarans.

This page intentionally left blank.

# EXECUTIVE SUMMARY

*A model of a high speed trimaran seatrain concept was tested for resistance, statics, and controllability. The seatrain, of identical trimaran units developed from the original NSWC Carderock Division connector-less concept, was proposed by CSC as a solution for the America's Marine Highway initiative. Four identical 10 foot long self propelled models were built for the purpose of measuring resistance of incrementally increasing in length seatrains. A series of towed and self-propelled model tests were used for characterizing the effect of the seatrain on propeller inflow velocities. Hull forces and moments developed at varying yaw angles were measured for validating maneuvering simulations produced by CSC. The models were then remotely controlled to demonstrate the operational capabilities of the yaw articulating seatrain. The design showed resistance reductions of up to 30% in comparison to a single unit in resistance while having minimal effect on the inferred propeller inflow velocities. The forces and moments were successfully measured and recorded for simulation verification purposes. A sea train of two and three units successfully demonstrated that a seatrain can be controlled and maneuvered through a number of typical ship operations. It was found however that simple controllability will require development of an interdependent autopilot system.*

# INTRODUCTION

Seatrains are longitudinal assemblies of similar sized hydrodynamic transportation units that increase the overall length resulting in a performance benefit to the system [Reference 3]. In short, by adding more units the train hopes to replicate the benefits of having an extremely long, slender hull form minimizing wave drag and therefore increasing efficiency and/or maximum speed.

This report presents the results of tests conducted at the Naval Surface Warfare Center, Carderock Division (NSWCCD) and the Tridelphia Reservoir on a seatrain model of up to 4 high speed trimarans (HST). The model tested was designated as model 5714.The high speed trimaran models are 1:54.13 scale representations of a hullform developed at Computer Sciences Corporation(CSC) in conjunction with the NSWCCD. The HST concept described herein was intended as a possible solution for the America's Marine Highway initiative.

## Background

### *America's Marine Highway*

Thc America's Marine Highway (AMH) initiative is a Department of Transportation (DOT) program that intends to expand the development of freight service operations carrying either containerized or trailer cargo throughout the United States. The program looks to increase the utilization of the navigable waterways around the U.S. and integrate them with current land transportation by means of a "inter-modal" system. With a developed AMH the DOT hopes for "reliable, regularly scheduled, competitive, and sustainable services"[Reference 1] that employs U.S. ships. A seatrain was proposed by CSC as a solution for AMH.

### *Historical Seatrains*

The HST seatrain is a further step in the research of the capabilities and benefits of seatrain use. The previously model tested connectorless seatrain concept[Reference 3] was done to examine thc possibilities of improved austere-port acccssible ships to increase range and speed.

Previous model tests were conducted at the University of Michigan and Stevens Institute of Technology* to illustrate a speed improvement of small amphibious vessels by traveling in close proximity while arranged in a tandem configuration. It was shown that the resistance of the lead unit is much greater than that of subsequent units. As a system however, the total resistance had reduced and it was determined that multiple small amphibians could improve the transit speed by traveling, connected together, in tandem. This concept of hydrodynamic drafting has inspired larger scale concepts of high-speed seatrains.

The US Navy's experience with multiple connected platforms and associated connector loads is the Improved Navy Lighterage System (INLS) [Reference 2]. This system links multiple units together, each approximately 90 ft long, to produce a rapidly deployable floating causeway. The loads on the connectors, called flexors, can be as much as the weight of a single unit. One of the most critical flexor loading conditions is the operation in quartering seas. The flexor connectors located outboard on port and starboard sides at the fore and aft ends of the modules, restrain the longitudinal tension between units. These flexors keep the units from separating and restrain the yaw moments produced by uneven lateral loadings. Due to the unbalanced moment arms created by the long slender hulls, the flexor connectors experienced high tensile loads introduced by restraining the yaw moments*.

Another relevant USN project was the Mobile Offshore Base (MOB) in which several platforms with small-waterplane-area floats were assembled together to form a huge floating air-field and supply center [Reference 4]. The MOB was a very low speed concept and the connector loads were mainly caused by seaway induced motions. Connector loads were determined for several conceptual connector designs using analytic predictions along with sea keeping model results. In the MOB project, all modules were rigidly constrained to be at the same deck level to provide a continuous runway. The rigid connections proved to contribute to the demise of the MOB concept due to the inability to manage the large impulse generated by wave action. It was found that flexible connectors (mass-spring-damper system) were required in order to handle the large impulse loads*. The experience in both the INLS and the MOB program points out the importance of connector flexibility with regard to the management of connector loads.

Most recently, model testing was done on the "connector-less seatrain concept", a system designed to explore the benefits and possibilities of operating a seatrain without connectors given realistic levels of power [Reference 3]. The geometry of the ships was designed from the beginning with the seatrain in mind. The design consisted of a V-shaped hull with a notch cut in the center of a wide transom. This design needed improvement with respect to upright stability and accommodating yaw motion between the units.

## Objectives

NSWCCD was primarily tasked with demonstrating that a seatrain, given the freedom of yaw articulations between individual units, can be turned and maneuvered while allowing for freedom in yaw of the individual units. The 'operational demonstration' documented in this report is NSWCCD's approach using a combination of connectors, control algorithms for aft unit(s) propulsion and steering, and remote control operation of the forward unit on the Tridelphia Reservoir. Though not a primary objective, NSWCCD recorded loads between the sea train operations and attempted to document the characteristics of the seatrain's turning path.

In conjunction with the operational demonstration, towing tank tests were done to measure a number of hydrodynamic factors. The primary objective was to determine the resistance magnitude

*This information is contained in proprietary reports

and distribution of the sea train with varying number of units and outrigger positions. Using this information, the effectiveness of transporting the seatrain load, represented by the transport factor, can be compared against systems with comparable missions. This data provides guidance for propeller selection and friction calculation for successive seatrain units. NSWCCD established a method using shaft rpm to characterize the inflow into each successive unit's propellers due to the wake of the preceding hullform(s) and propeller wash. The body forces and moments of the units in a seatrain were measured in order to support development of seatrain maneuvering simulations conducted by CSC. The loads were measured for a single unit across a range of yaw angles with zero rudder angle as well as zero yaw angle with a range of rudder angles. The measurements of varied yaw angles were conducted for the model both free and fixed in heave, pitch, and yaw. The hydrodynamic loads were then measured on each rigidly mounted model in a three unit seatrain with varying drift angles on the first and last units of the seatrain.

A summary of the objectives is given below.

- Turning Demonstration
  - Demonstrate that an effective distribution of propulsion and steering can be maintained during operations
  - Record the loads between units during seatrain operations including straight ahead powering and turning [1]
  - Document[1] and demonstrate the characteristics of the turning path
- Resistance Test
  - Estimate the reduction in required horsepower needed on individual ships in calm water as the result of varying number of units in the seatrain.
  - Predict the transport factor of the system to compare against other systems
  - Determine the distribution of total seatrain power to provide a seatrain that will not separate during operations
- Longitudinal Flow through the Propeller Plane
  - Characterize the effects on inflow into each successive propeller due to the wake of the preceding hullform(s) and propeller wash.
- Body Forces & Moments of Captive Units
  - Determine the hydrodynamic loads on each unit with varying range of drift angles on the first and last units of the seatrain.
  - Determine the hydrodynamic loads on an independent unit with varied rudder angle
  - Acquire data to support development of a seatrain maneuvering simulation

[1]Secondary Objective

# HULL & MODEL DESCRIPTION

The four high speed trimaran seatrain models were constructed by NSWCCD. The models are designated by the NSWCCD model numbers: 5714-1, 5714-2, 5714-3, 5714-4. Figures 1a and 1b are photographs of two of these models positioned in a tandem configuration. The center-bodies of ships were painted different colors (white, orange, yellow, and grey) to differentiate the hulls. The side hulls were constructed in the same mold using a poured foam. The propeller shafting was supported inside the mold and the foam was allowed to cure around it. The side hulls were all painted white for contrast with the center hulls.


(a) Bow view (b) Aft view

**Figure 1: High Speed Trimarans in seatrain configuration represented by 5714-1 and 5714-2**

The final hullform geometry was created by CSC, the body plan can be seen in Figure 2. A cylindrical bow was adopted above the water line for a unit interface that permits relative rotation. The trimaran provides improved deck area and most importantly, increased deck width for cargo manipulation. The model was built to a scale ratio ($\lambda$) of 54.134 making the model 10 feet long in order to meet multiple restrictions. The model size was chosen large enough to support the equipment necessary for radio controlled operational demonstrations but constrained by the size of the towing tank, the length of the carriage towing strut, and the budget available to the project. The particulars of the hull are given in Table 1. A larger body plan and side view is in Appendix H.

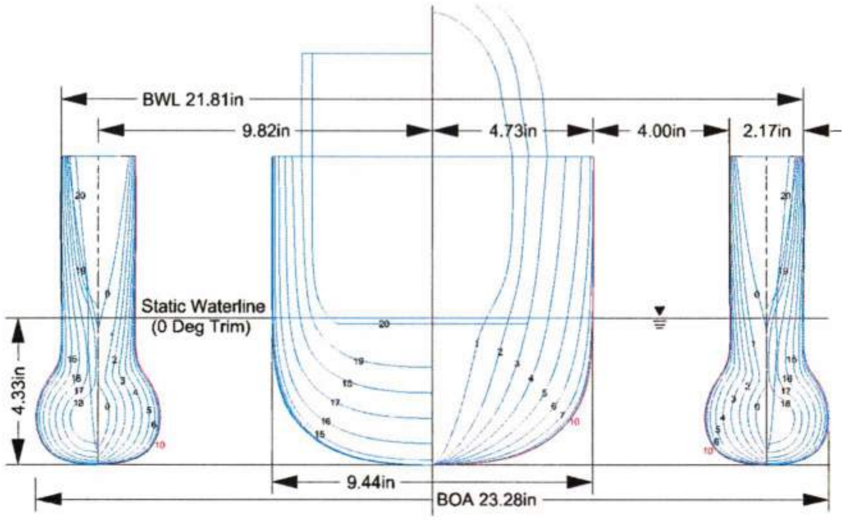


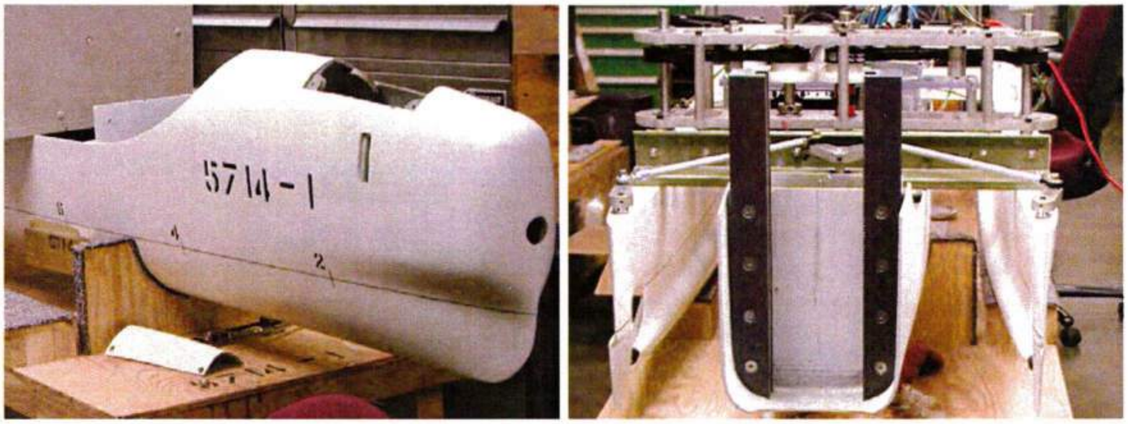

**Figure 2: Model 5714 body plan**

**Table 1: Full and model-scale particulars for $\lambda = 54.134$**

| | Ship Scale | | Model Scale | |
|---|---|---|---|---|
| | Center Hull | Side Hull (one) | Center Hull | Side Hull(one) |
| LOA | 541 ft | 315 ft | 10 ft | 5.82 ft |
| LWL | 540 ft | 252 ft | 9.97 ft | 4.85 ft |
| Beam | 42.65 ft | 16.4 ft | 0.79 ft | 0.30 ft |
| Draft | 19.5 ft | 19.5 ft | 0.36 ft | 0.36 ft |
| Displacement | 7933 LT | 1347.5 LT | 108.98 lb | 18.51 lb |
| Wetted Area | 30858 ft$^2$ | 12778 ft$^2$ | 10.53 ft$^2$ | 4.36 ft$^2$ |

The center hulls were constructed from a female mold using fiberglass. Fiberglass bulkheads and platforms were added for structural stiffness and mounting locations for instrumentation. The design was created for complete freedom of yaw, pitch, and heave between units. Due to model limitations yaw was restrained to ($\pm 15°$), pitch ($\pm 10°$), and heave ($\pm 4$ inches). In a displacement ship pitch and heave are large factors in the resistance of the vessel and allowing for each individual unit to reach their optimal pitch and heave without direct influence from hull to hull is a necessary part of the design. The flexibility in yaw is intended for reducing forces between units and the turning diameter of the train. The bow was rounded to allow for pivoting and a large surface area to distribute the load (Figure 3a). Below the waterline, the bow is slender with a nearly straight stem. The stern was designed for a large amount of relative heave displacement (Figure 3b). The hole at the bow of the model and the grey plastic tracks on the stern were model testing artifacts for the operational demonstration and for

accommodating dynanometry to monitor loads between units. For the turning demonstration a gimbal was placed in the stern between the vertical tracks giving the ships freedom in heave, yaw, and pitch (Figure 3b and Figure 4).




(a) Bow view (b) Aft view

**Figure 3: Bow and stern design for HST connector-less seatrain**

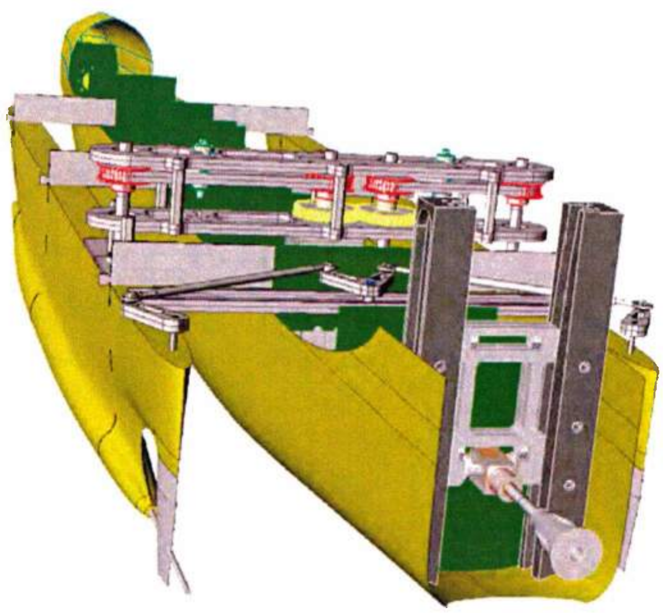


**Figure 4: Rhino 3D rendering of gimbal system**

The interface between hulls was designed for approximately 8.9 feet of overlap (1.98 inches model scale). This results in a small sectional area overlap due to the reduced sectional area fore and aft

on each vessel. The sectional area of each vessel and of the total train in a three unit seatrain as a percentage of the maximum sectional area is shown in Figure 5. The dashed orange line illustrates a more continuous section area curve representative of a long slender hullform. The sum of the section area curve below is the section area curve of the entire train and indicates large discontinuities along the length. Previous results have shown [Reference 3] that the greatest resistance benefits for seatrain designs are from large sectional area curve overlaps, which results in a smoother more continuous sectional area curve transition from one unit to another.

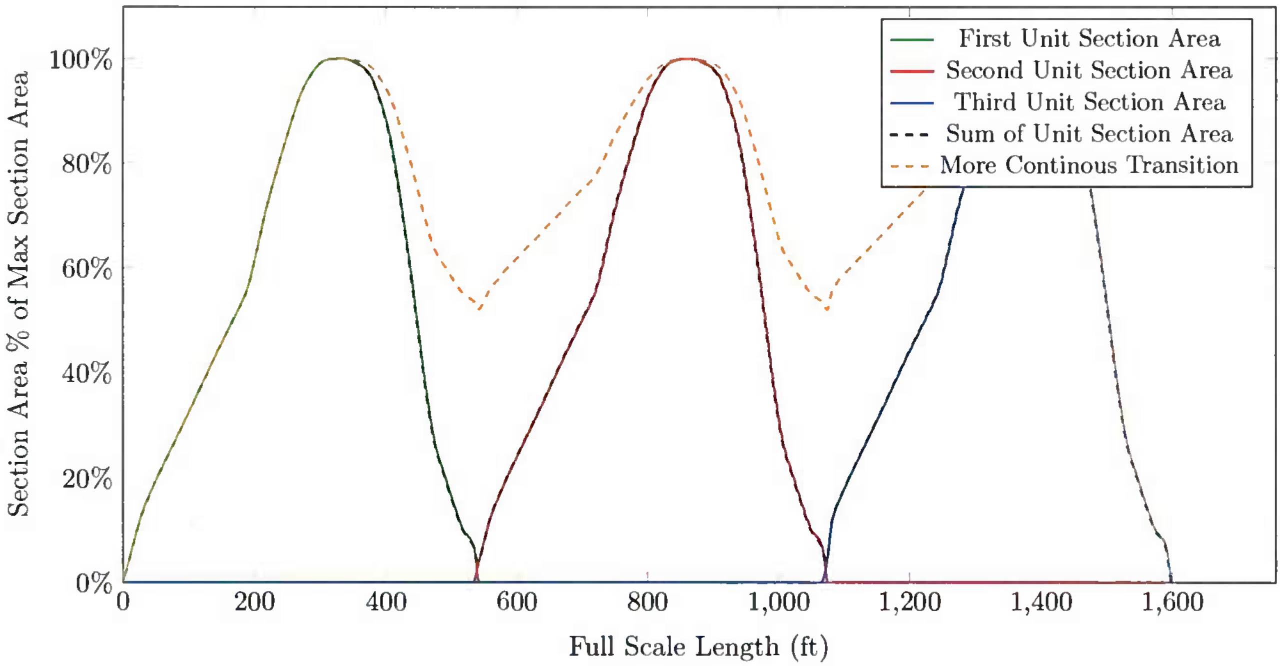



**Figure 5: Section area of seatrain along length**

Side hull propulsion units were chosen in the design of the vessel with the intent of mitigating any additional resistance on the following unit due to the propeller wash. Motors were placed in each side hull to provide self propulsion for each unit. The side hulls were built using a split mold with foam encapsulating a right angle gearbox and allowing for the propeller shaft and rudder tube to extend vertically above the hull. The rudder control arms and the motor gearing can be seen in Figure 3b.

## DATA ACQUISITION AND INSTRUMENTATION

The tests were conducted using Models 5714(-1 through -4) in both the Carriage II - Deep Water Basin and the Tridelphia Reservoir. CompactDAQ chassis (NI cDAQ-9188) and National Instruments C series modules were located in each model (Figure 6), and the data was digitized on-board and collected through a router by the data acquisition computer. The propeller shaft speeds were collected using the internal motor encoders paired with NI 9402 Digital Counter/Timers. Shaft torques were measured from the current output of the motor controllers and collected through NI 9239 Analog input modules. The carriage testing and operational demonstration required different instrumentation and final data acquisition methods. The basic description of instrumentation for each set of tests is

described below. A complete list of instrumentation and positions can be found in Appendix H.

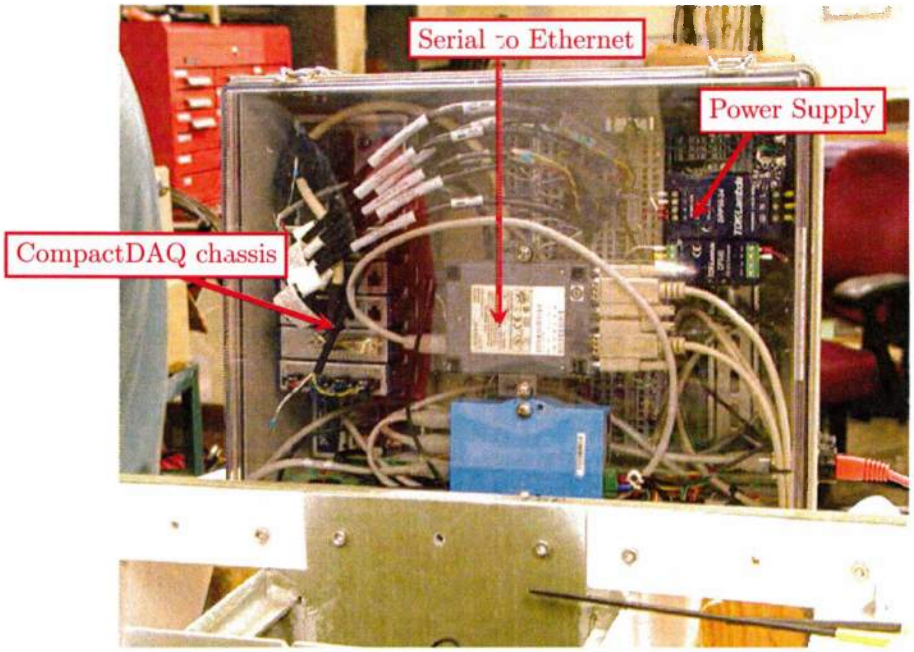



**Figure 6: Onboard data acquisition system and control box**

## Carriage II - Deep Water Basin Measurement System

In addition to the aforementioned instrumentation, additional instrumentation was added during testing on Carriage II. The data during carriage runs were collected using Code 8500 LabVIEW (Laboratory Visual Information Engineering Workstation) Data Collection software on a carriage-mounted computer connected by a CAT5 network cable to the CompactDAQ chassis.

### *Calm Water Resistance*

Resistance of each model was transmitted from a block gauge with a Macro Sensor HSD 750-015, a hermetically sealed DC-LVDT position sensor through a NI 9239 analog input module in the compactDAQ chassis. The sinkage of the model was measured by using string potentiometers transmitted through the NI 9239 analog input module as well. The models were free to heave, pitch, and roll, but restrained in surge, sway, and yaw.

### *Longitudinal Flow Through The Propeller Plane*

The size of the models restricted the maximum propeller size. At the model scale propeller size, the Reynolds number is below the turbulent threshold for proper powering experiments (see Equation

1).

$$
\begin{aligned}
V_{R,0.7R} &= \sqrt{V_{model}^2 + V_{t,0.7R}^2} \\
&= \sqrt{2.720^2 + 2.566^2} = 3.739 ft/s \\
R_n &= \frac{V_R C_{0.7R}}{\nu} \\
&= \frac{3.739 \cdot 0.0952}{1.07 \cdot 10{-5}} = 3.327 \cdot 10^4 \\
R_n(\text{turbulent}) &\geq 5 \cdot 10^5 \qquad (1) \\
V_{model} &= \text{Velocity of model in ft/s} \\
V_{R,0.7R} &= \text{Resultant velocity of propeller at 70\% of radius} \\
V_{t,0.7R} &= \text{Tangential velocity of propeller at 70\% of radius} \\
C_{0.7R} &= \text{Chord length of propeller at 70\% of radius} \\
\nu &= \text{Kinematic Viscosity of freshwater}
\end{aligned}
$$

Instead, since relative values are needed, the average flow through the propeller plane was determined by collecting the rpm of a free spinning propeller with an internally hub mounted magnetic pickup developed and built in-house (Figure 7). When the propeller was spun by inflow velocity a pulse was generated and then collected using a NI 9402 Digital Counter/Timer Module. Absolute values of velocity wre not attainable because open water calibrations were not conducted due to the relative nature of the objective.

**Figure 7: Propeller with magnetic pickup**

### Tridelphia Reservoir - Operational Demonstration Measurement System

The data from the CompactDAQs in each unit was collected through a router by an onboard computer located in the forward unit. Latitude and Longitude of the forward vessel was measured using a Crossbow GPS unit. Yaw rates and headings were measured using triaxial magnetometers and gyros mounted aboard each vessel. The information collected was used to plot the course and speed over ground of the total sea train. The forces between the models were monitored and collected using AMTI six-component load cells, collected using 2 four channel NI 9237 Bridge Modules. The hulls were connected via a gimbal, seen in Figure 4. The gimbal allowed for freedom of angular displacement but restricted the relative longitudinal translation motion between the hulls. The gimbal also had the option to lock in one of the three angles. The articulating connection design replicates the designed connectorless seatrain concept until the physical limit of the gimbal was reached. The design isolates the relative forces and minimizes the moments between the hulls until the limit was reached.

## EXPERIMENTAL PROCEDURES

Froude scaling was employed in order to maintain wave resistance similitude. This gave the model scale speeds as defined below.

$$F_n = \frac{V_s}{\sqrt{gL_s}} = \frac{V_m}{\sqrt{gL_m}} \tag{2}$$

The model scale speeds ranged from 2.30 - 9.16 ft/s representing a full scale of range from 10-45 knots.

### Carriage II - Deep Water Basin Test

Each model was attached to the carriage using tow posts mounted to the underside of Carriage 2 (Figure 8) and the previously discussed rod, gimbal, and track was removed. Running pitch angles were measured with string potentiometers near the models' aft and fore perpendiculars (AP, FP). The presented pitch angles and heaves are given in relation to the static, at-rest model conditions.

A single ballast condition of 10,628 long tons full scale and 146 pounds model scale was achieved. Even keel and $-1°$ trim by the stern static trim conditions were evaluated. The tests iterated in the following subsections were done on the carriage with multiple data collects per run.

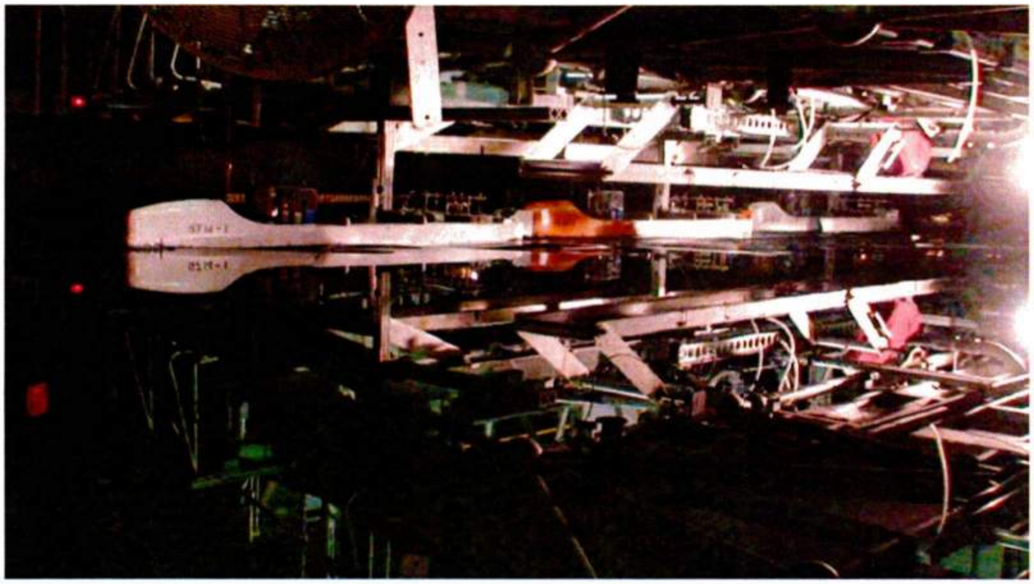


**Figure 8: Carriage 2 with three models attached**

### *Calm Water Resistance*

The testing was done by running the first model independently to establish a baseline. Since the resistance of a trimaran vessel can vary dramatically with the location of the outriggers, the model was run at the full range of speeds with three distinct outrigger positions.

- Outriggers in middle position on even keel
- Outriggers in aft position on even keel
- Outriggers in middle position on $-1°$ trim

The aft outrigger position was 10.91 inches(49 feet full scale) aft of the default middle position and can be seen in Figure 9. The configuration having the least resistance was utilized for the seatrain tests with incrementally varying length. The next three models were added incrementally, with all units with even keels and the outriggers in their middle positions. The models were positioned and attached to the carriage so that the bow and stern overlapped to the design 1.98 inches, but unattached so that each was able to roll, pitch, and heave independently of one another. Speeds were run at increments equivalent to 2 knots full scale with additional points added during testing to accommodate inflections in the resistance curves. The calm water resistance test agenda is shown in Table 2.

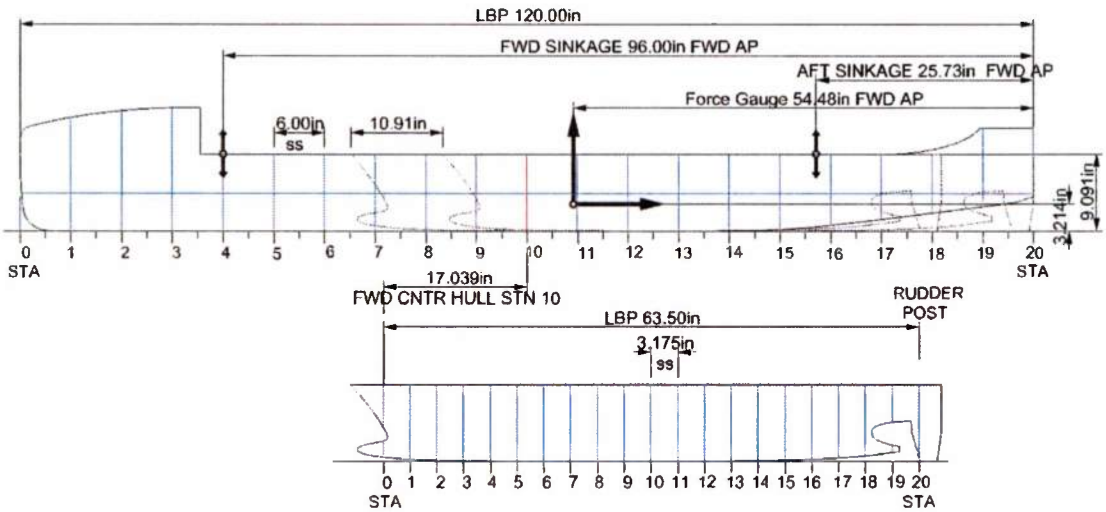



**Figure 9: Model 5714 spacing and layout**

**Table 2: Test agenda for calm water resistance**

| TEST | CONFIGURATION | SPEEDS | ARRANGEMENT |
|---|---|---|---|
| 1 | Single Unit Train | 10-45 kts | Middle Outrigger Position |
| 2 | | 10-40 kts | Middle Outrigger Position, $-1°$ trim |
| 3 | | 10-40 kts | Aft Outrigger Position |
| 4 | Two Unit Train | 10-40 kts | Middle Outrigger Position |
| 5 | Three Unit Train | 10-40 kts | Middle Outrigger Position |
| 6 | Four Unit Train | 10-40 kts | Middle Outrigger Position |

### *Longitudinal Flow Through The Propeller Plane*

The testing was performed to determine the influence of the forward units on the following units' side hulls with regards to flow through the propeller plane. A simple measurement technique using a freewheeling propeller was adopted for the measurement. The method comes from the WWII era of model testing, where free-wheeling propellers were used to measure propeller inflow velocities. In today's model testing environment laser based measurement techniques are used to obtain propeller inflow characters with enough fidelity for propeller design studies. For the purposes of this test the free-wheeling rotor technique was suitable to satisfy the objectives. The RPM of a freewheeling rotor tends to be linear with average inflow, thus a percentage change in RPM can be equated to a percentage

change in average inflow speed. The bearing friction and shaft alignment are assumed to be irrelevant due to the comparative nature of the experiment. The forward speed of the vessels was incremented from 10-34 knots in 2 knot intervals.

The following configurations were tested with a freely spinning propeller. The agenda is in Table 3.

- An independent unit to establish a base line
- One unit's free spinning propeller rpm measured at a time in a 4 unit train without propellers installed on the other hulls
- One unit's free spinning propeller rpm measured at a time in a 4 unit train while units forward of the measured unit are powered to the model self-propulsion point (0 net drag)

**Table 3: Test agenda for longitudinal flow through propeller plane**

| TEST | CONFIGURATION | SPEEDS | ARRANGEMENT |
|---|---|---|---|
| 30 | Independent Unit | 10-45 kts | All Units Unpropelled (one free-wheel) |
| 8 | Lead Unit of Four | 10-34 kts | |
| 7 | Second Unit of Four | 10-34 kts | |
| 25 | Third Unit of Four | 10-34 kts | |
| 27 | Fourth Unit of Four | 10-34 kts | |
| 28 | Third Unit of Four | 10-34 kts | Forward Units Propelled (one free-wheel) |
| 29 | Second Unit of Four | 10-34 kts | |

### *Body Forces & Moments*

The test objectives required static model forces be measured to support development of a seatrain maneuvering model being developed by CSC. The hulls were run at three speeds from 10 to 30 knots for each condition. The first hull was run independently at varying yaw angles from 0 to 10 degrees while the model was free in heave, trim, and roll and again where it was fixed. Additionally a three unit configuration was examined while so the first and third units were oriented with non-zero distinct yaw angles. The first unit was yawed from 0 to 10 degrees (Figure 10a) and then the third unit (Figure 10b), and finally both units were yawed in opposite directions (Figure 10c). To determine the body forces generated by the rudder, one model was run independently at zero degree yaw while varying the rudder angle through ±30 degrees. The agenda for the Body Forces & Moments is presented in Table 4.

(a) First unit yawed

(b) Third unit yawed

(c) First and third unit yawed

**Figure 10: Configurations of yawed three unit seatrain**

Table 4: Test agenda for body forces and moments

| TEST | CONFIGURATION | SPEEDS | ARRANGEMENT |
|---|---|---|---|
| 9 | Single Unit Free Sink, Trim & Roll | 10-45 kts | 0 Deg Yaw |
| 10 | | 10-30 kts | 5 Deg Yaw |
| 11 | | 10-30 kts | 10 Deg Yaw |
| 12 | | 10-30 kts | 2.5 Deg Yaw |
| 13 | | 10-30 kts | 7.5 Deg Yaw |
| 14 | Single Unit Fixed Sink, Trim & Roll | 10-40 kts | 0 Deg Yaw |
| 15 | | 10-30 kts | 5 Deg Yaw |
| 16 | | 10-30 kts | 10 Deg Yaw |
| 17 | Three Unit | 10-40 kts | All 0 Deg Yaw |
| 18 | | 10-30 kts | First $-5°$ |
| 19 | | 10-30 kts | First $-10°$ |
| 20 | | 10-30 kts | Last 5° |
| 21 | | 10-30 kts | Last 10° |
| 22 | | 10-30 kts | First & Last 5° |
| 23 | | 10-40 kts | First & Last 10° |
| 24 | Single Unit Fixed | 10-40 kts | Rudder $\pm 0, 5, 10, 20, 30°$ |

## Tridelphia Reservoir - Operational Demonstration

The models were attached using the aforementioned gimbal and the first vessel was wired for remote control operation. Tests were conducted using the same loading and displacement as the carriage testing. Up to three units were used during the demonstration. Figure 11 shows a two unit assembly. The forward unit was controlled remotely by test personnel. The aft units were controlled via an onboard algorithm which utilized the forces and moments from each unit's forward linkage to command rudder angles and propeller thrust attempting to achieve zero forces and moments (Figure 12). The control algorithm required fine tuning to maximize the ability to control the ship. If responses to forces were large, the ship was highly maneuverable but hard to control in a straight line. If the control response was minimal, response to input was slow and difficult. The operational demonstration test agenda is shown in Table 5.

**Figure 11: Two unit seatrain maneuvering demonstration**

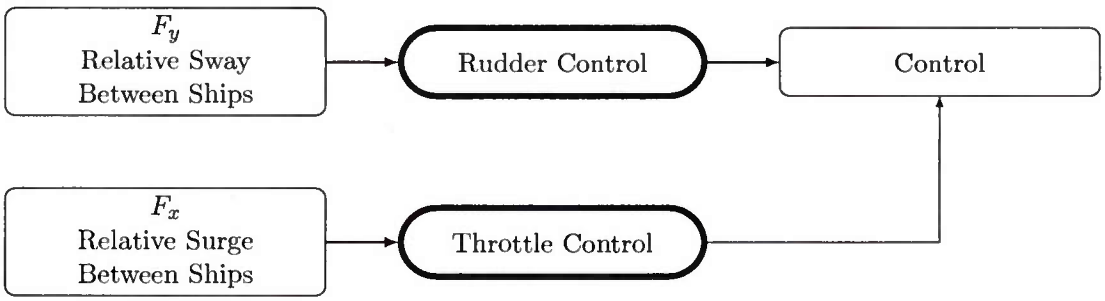



**Figure 12: Unit control algorithm**

**Table 5: Test agenda for operational demonstration**

| TEST | CONFIGURATION | SPEEDS | ARRANGEMENT |
|---|---|---|---|
| 40 | Single Unit Train | 3 Speeds | Rudder $5, 10, 20, 30°$ |
| 41 | Two Unit Train | | |
| 42 | Three Unit Train | | |
| 43 | Two Unit Train | | |
| 44 | Three Unit Train | | |
| 45 | Three Unit Train | | |
| 46 | Three Unit Train | | |
| 47 | Single Unit Train | | |

# ANALYSIS

## Carriage II - Deep Water Basin Analysis

All tow tank data was analyzed using a series of faired data points for full scale calculations. Faired data was generated using the LabVIEW "NURBS fairing" program (version 1.0.854). This program works symbiotically with the engineer to develop fits to data without being restricted by standard mathematical models through fitting splines to the data set. This process allows the engineer to systematically remove outliers without manually removing data and reducing the goodness of fit.

### *Calm Water Resistance*

The method for determining the friction on a seatrain is slightly more complex than a single hull due to the development of the shear layer from hull to hull. By having the hulls in such close proximity the shear layer will grow over the entire length as if the entire train was one hull and also causes the shear layer to affect each model's individual value of skin friction differently. This shear layer growth is graphically illustrated in Figure 13.

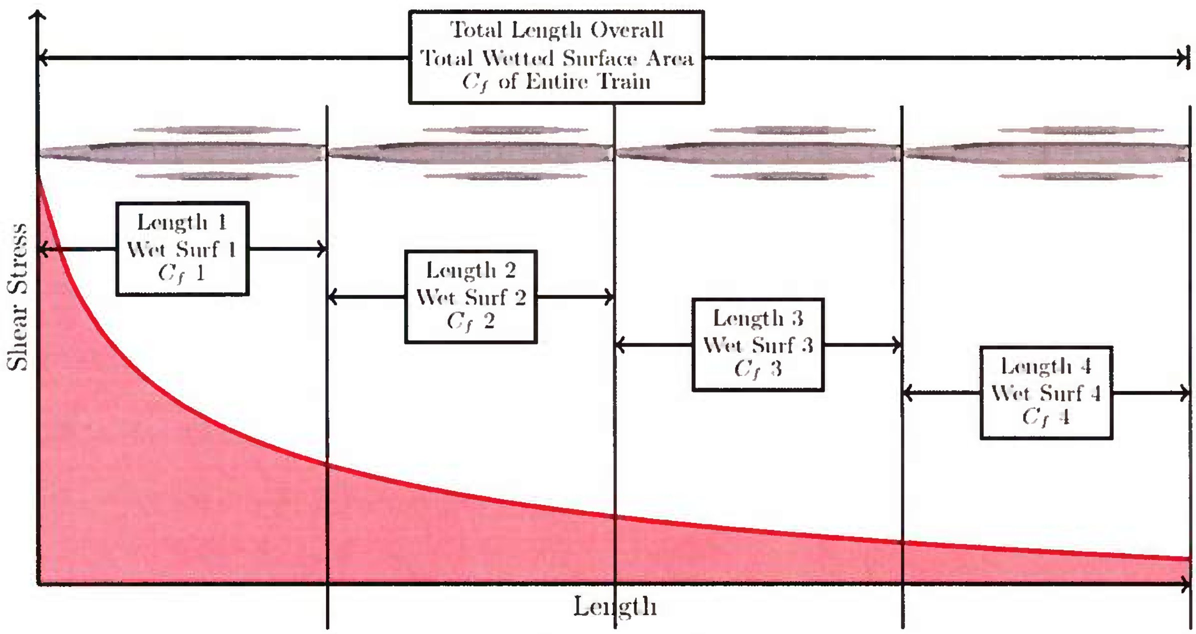



**Figure 13: Shear layer growth over a seatrain**

Analysis is done by associating the friction component of each of the units as being a section of a much longer hypothetical monohull. A complete discussion of the analysis methods for scaling of seatrain resistance can be found in Appendix A.

The analyzed results were curve fit using a Non-uniform rational B-spline (NURBS) program developed in LabVIEW by Code 8500 personnel. NURBS allows for more complex curves than common mathematical models which is ideal for resistance curves that may have multiple inflection points.

The resistance tests were then presented in terms of effective horse power ($EHP$), lift-to-drag ratio

$(L/D)$ and Transport Factor $(TF)$. EHP is a combination of speed and resistance.

$$EHP = \frac{R_T V_{ft/s}}{550} hp \tag{3}$$

Lift to Drag ratio of the entire system is a ratio of the total resistance of the system to the total displacement of the ships, creating a ratio where higher values represent better performance.

$$L/D = \frac{\sum_{n}^{m} \Delta_n}{\sum_{n}^{m} R_{Tn}} \tag{4}$$

$m$ = Number of units in Seatrain

$\Delta_n$ = Displacement of unit 'n' in Seatrain

$R_{Tn}$ = Total Resistance of unit 'n' in Seatrain

Transport factor is a ratio based on the lift drag ratio multiplied by the propulsive efficiency $\eta_D$.

$$TF = \eta_D \frac{L}{D} \tag{5}$$

$\eta_D$ = propulsive efficiency

An assumed propulsive efficiency of 0.7 was used for all calculations.

### *Longitudinal Flow Through The Propeller Plane*

The longitudinal flow required minimal analysis as RPM was a direct output of the instrumentation. RPMs were curve fit using a sixth order polynomial. Data is then presented as a ratio of the RPM of the propeller versus the RPM of a free-spinning propeller on an independent unit.

### *Body Forces & Moments*

For each unit in the train an nominal coordinate system has to be defined to maintain consistency in comparison between the units. Because of cross flow and other complications in scaling, all moments and forces are presented in model scale units. Due to the mounting system of the units onto the carriage all forces are oriented in the global reference frame rather than local. The coordinate system for the forces and moments on an individual unit can be seen in Figure 14.

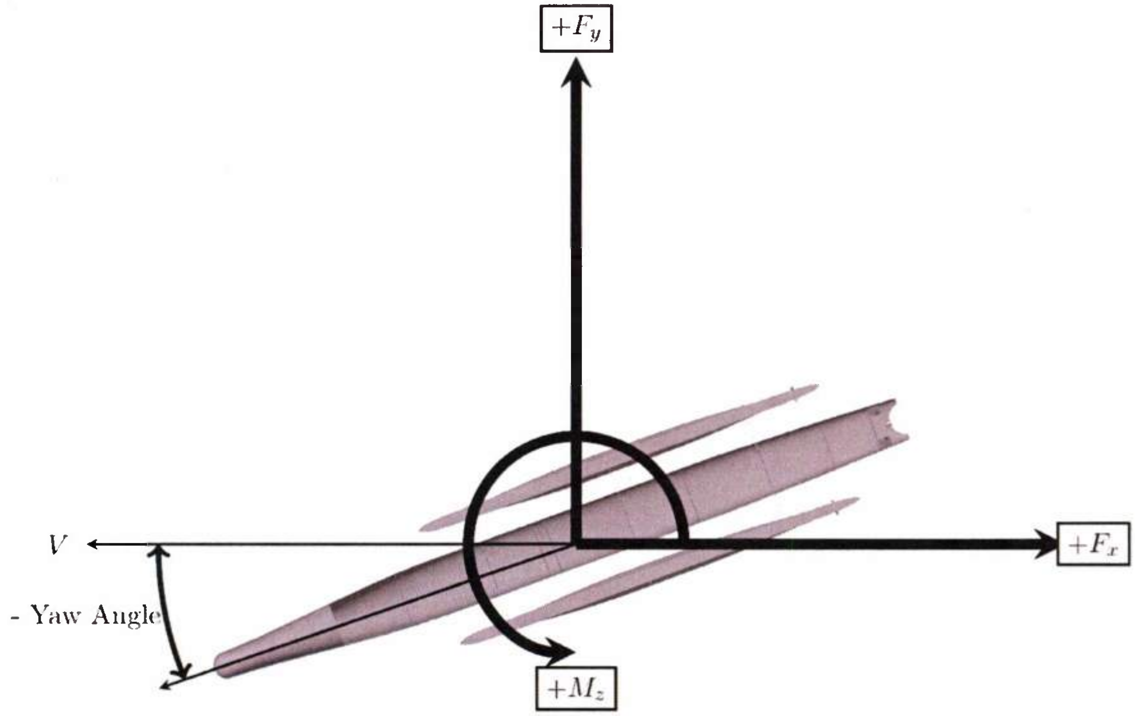



**Figure 14: Trimaran force moment diagram**

$F_z$ is directly vertical and the other moments are along their respective axes with the right hand rule. All forces and moments were fit using fourth order polynomials.

## Tridelphia Reservoir - Operational Demonstration Data Analysis

The operational demonstration was analyzed as time resolved data at the 5 Hz update rate, no curve fitting was used in this analysis.

### *Course Over Ground*

Latitude and longitude was recorded at a different data rate than the rest of the system. Course over ground was only examined when new values were received from the GPS. The aft units' positions then have to be derived from the forward unit's location and each units' respective yaw angles. The relative yaw angles were derived from the headings received by modules mounted 2 feet aft of the

bow and 8 feet forward of the transom. Figure 15 shows the basic positions and nomenclature. This information and the following equations were used to find the positions of the three vessels.

$$
\begin{aligned}
&\textbf{Unit 1 Position}\\
&X_1 = X_1(\text{from GPS})\\
&Y_1 = Y_1(\text{from GPS})\\
&\theta_1 = \theta_1(\text{heading})\\
&\textbf{Unit 2 Position}\\
&X_2 = X_1 - 8\sin(\theta_1) - 2\sin(\theta_2)\\
&Y_2 = Y_1 - 8\cos(\theta_1) - 2\cos(\theta_2)\\
&\textbf{Unit 3 Position}\\
&X_3 = X_2 - 8\sin(\theta_2) - 2\sin(\theta_3)\\
&Y_3 = Y_2 - 8\cos(\theta_2) - 2\cos(\theta_3)
\end{aligned}
\tag{6}
$$

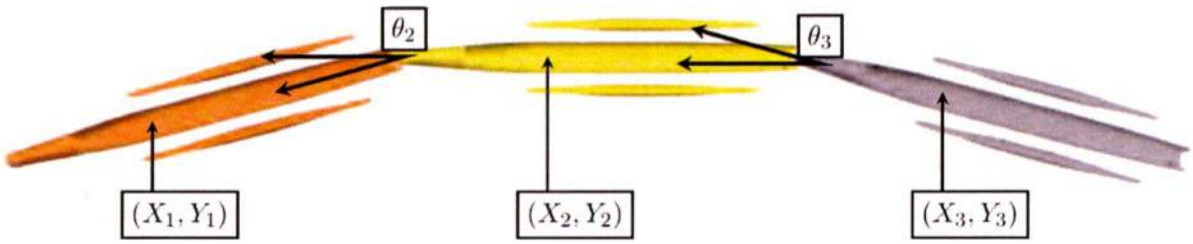



**Figure 15: Connected seatrain force moment diagram**

***Relative Forces & Moments***

The measured forces and moments for the connected train were the relative forces and moments between the hulls. The 6-axis load cell was mounted in the aft vessel of the linkage so all measurements were in the local reference frame of the aft vessel. Positive $F_z$ indicates compression, positive $F_y$ indicates that the aft vehicle was trying to sway farther starboard than the forward vehicle. The moments were along their respective axes.

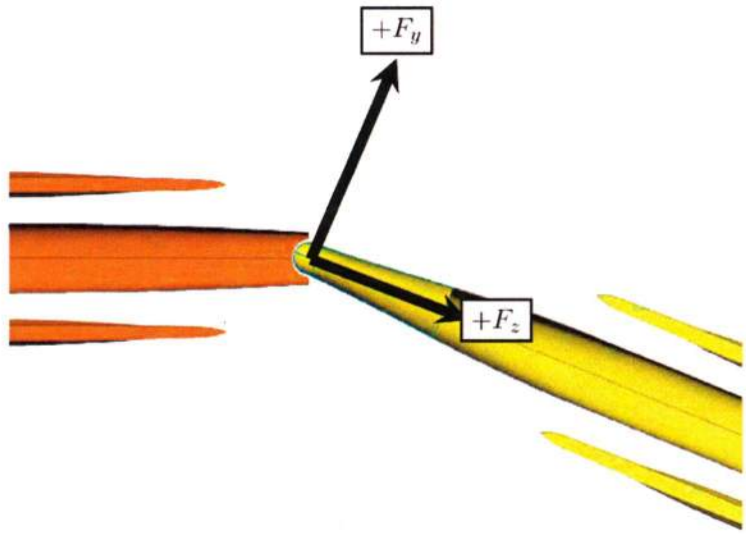



**Figure 16: Connected seatrain force moment diagram**

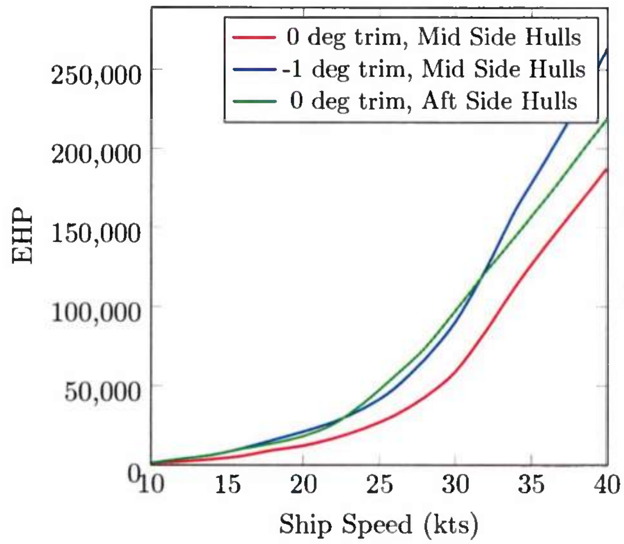
All forces and moments were processed using the calibration coefficients and interaction matrices and presented as time resolved data.

# EXPERIMENTAL RESULTS

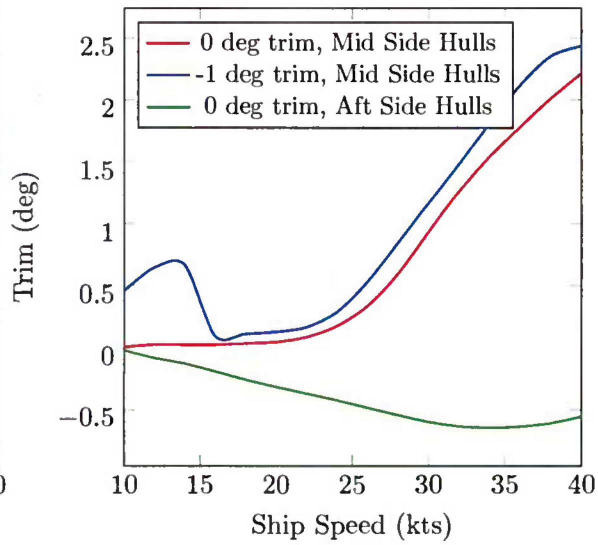
## Carriage II - Deep Water Basin Results

### *Calm Water Resistance*

The first three tests showed the differences in resistance between various configurations of a single hull, including a baseline 0° degree trim (even keel) with the side hulls in the middle position, $-1°$ degree trim (stern down) with the side hulls in the middle position, and 0° degree trim with the side hulls in the aft position respectively. Graphs of their EHP and running trim can be seen in Figures 17a and 17b respectively. The baseline condition has the least resistance whereas the $-1°$ case is slightly higher with marginally higher levels of trim past 15 knots. In the aft side hull condition the trim is reduced indicating the positive moment (bow down) created from the side hulls.




(a) EHP



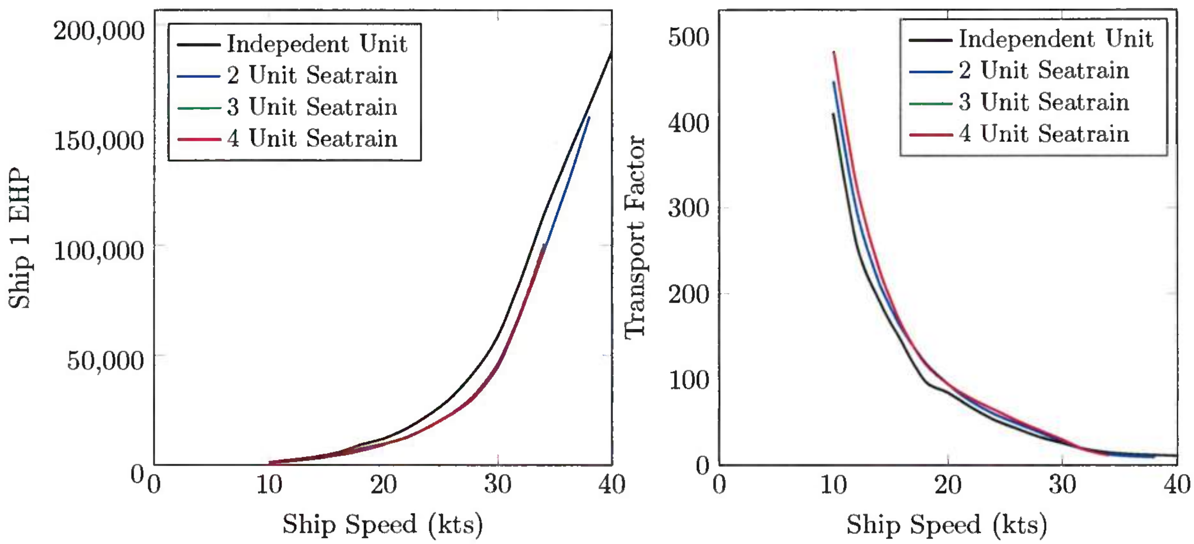

(b) Trim

**Figure 17: Comparison of three configurations of a single hull**

The subsequent tests added a hull for each sequential test until the train was four hulls long. The data obtained for each sequential test was then compared against the baseline condition (single unit train, middle outrigger position, 0° trim). Table 6 gives the full-scale predicted effective horsepower for the total train. Overall a quick improvement is seen when each hull was added, the transport factor increases by up to 40% when three ships were added to obtain a four unit seatrain. The first unit experiences improvements in EHP and transport factor with the second hull added, however as additional hulls are added, further improvements are minimal as seen in Figures 18a and 18b.

**Table 6: EHP of a seatrain of up to four units**

| $V_{ship}$ [kts] | One Unit [EHP] | Two Units [EHP] | Three Units [EHP] | Four Units [EHP] |
|---|---|---|---|---|
| 10 | 1,244.0 | 2,282.0 | 3,174.0 | 3,789.0 |
| 14 | 3,722.0 | 6,755.0 | 9,470.0 | 10,790.0 |
| 18 | 9,374.0 | 15,307.0 | 23,458.0 | 26,450.0 |
| 22 | 16,601.0 | 30,164.0 | 43,112.0 | 49,766.0 |
| 26 | 31,178.0 | 54,765.0 | 76,333.0 | 91,736.0 |
| 30 | 58,537.0 | 108,086.0 | 151,897.0 | 176,015.0 |
| 34 | 113,137.0 | 260,648.0 | 421,972.0 | 550,780.0 |
| 38 | 163,105.0 | 385,847.0 | | |




**(a) EHP** **(b) Transport Factor**

**Figure 18: Comparison of various length seatrains**

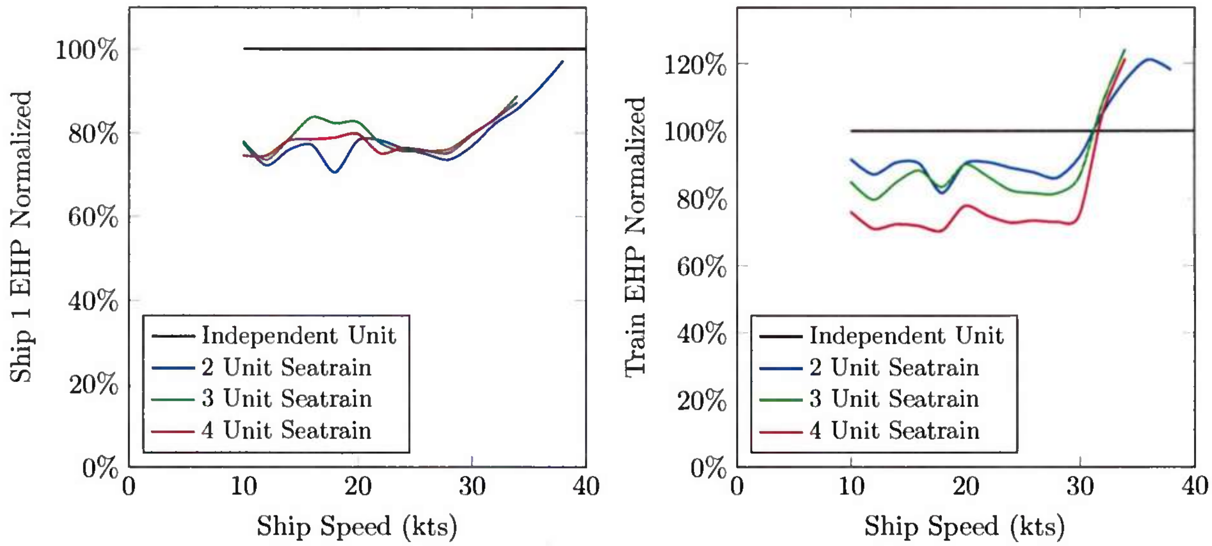
For easier visualization of the improvements, the entire train was normalized relative to a single hull to see the gains at each speed for adding on $n$ number of ships to the train (equation 7).

$$\text{Train EHP}_{normalized} = \frac{\sum_n^\infty EHP_n}{n \times EHP_1} \tag{7}$$

Figure 19a shows the effect of units 2, 3,and 4 on the resistance of the first ship. Figure 19b and Table 7 shows that a four unit seatrain reduced the total resistance percent by about 26.2% at speeds up to 30 knots.

**Table 7: Normalized EHP of total seatrain**

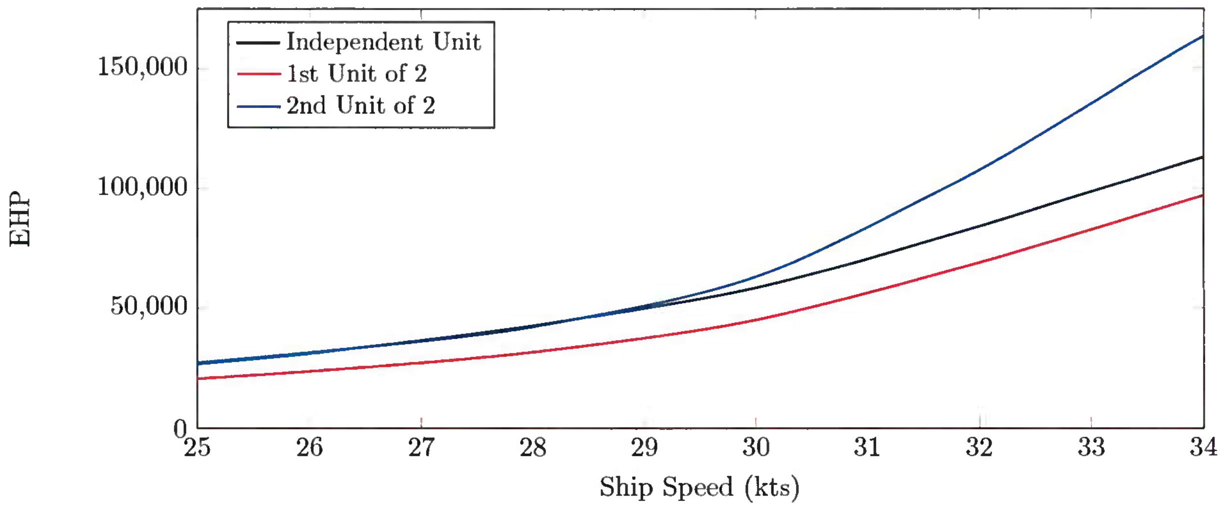
| $V_{ship}$ [kts] | One Unit [EHP%] | Two Units [EHP%] | Three Units [EHP%] | Four Units [EHP%] |
|---|---|---|---|---|
| 10 | 100.0 | 91.7 | 85.0 | 76.1 |
| 14 | 100.0 | 90.7 | 84.8 | 72.5 |
| 18 | 100.0 | 81.6 | 83.4 | 70.5 |
| 22 | 100.0 | 90.9 | 86.6 | 74.9 |
| 26 | 100.0 | 87.8 | 81.6 | 73.6 |
| 30 | 100.0 | 92.3 | 86.5 | 75.2 |
| 34 | 100.0 | 115.2 | 124.3 | 121.7 |
| 38 | 100.0 | 118.3 | | |



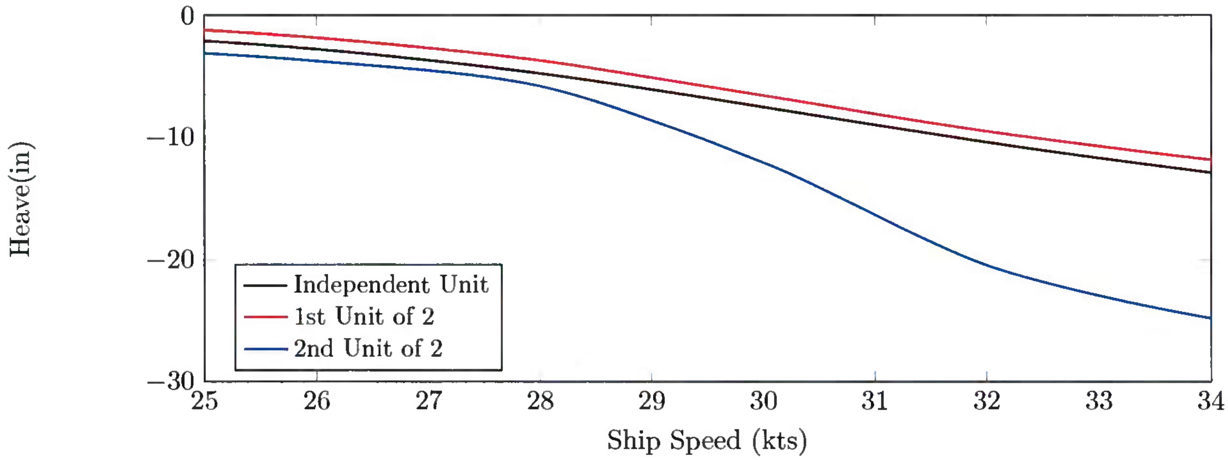

**(a) First ship's EHP normalized** **(b) Total train EHP normalized**

**Figure 19: Normalized EHP of various length seatrains**

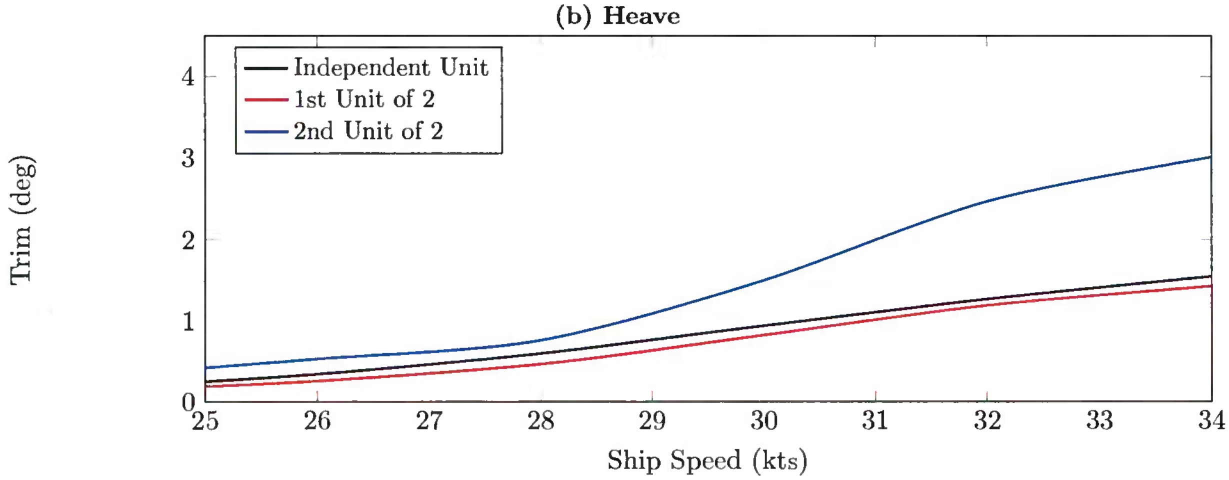
Figures 20 through 22 show the resistance, trim, and heave of each unit while operating as a two unit train, three unit train, and four unit train against a single unit over a critical speed range of 25 to 34 knots. As each additional unit in the train was added it can be seen that the forward most unit always maintained a reduced drag. When the train was comprised of two units, the forward unit sees a near constant reduction in drag and the aft unit's required horsepower increases after 29 knots (Figure 20a). The three unit seatrain showed that the first unit sees marginal improvement from the two unit train, the second unit's EHP is similar that of the first unit up to 30 knots, and the third unit has marginal improvement improvement from the baseline condition at up to 30 knots as well (Figure 21a). When the train was four units long the drag of all the units see improvement at speeds up to 31 knots (Figure 22a). All of these trends can be correlated with the heave (Figures 20b, 21b, and 22b) and pitch (Figures 20c, 21c, and 22c) of the individual units in the train. The resistance benefit disappears as the heave and pitch begin dramatically diverging from that of a single unit around 30 knots. The heave of the following units decreases while the trim increases. This high trim can be seen in Figure 23. A full listing of all results for the total train and individual units in the train can be found in Appendices B and C respectively.




**(a) Effective Horsepower**

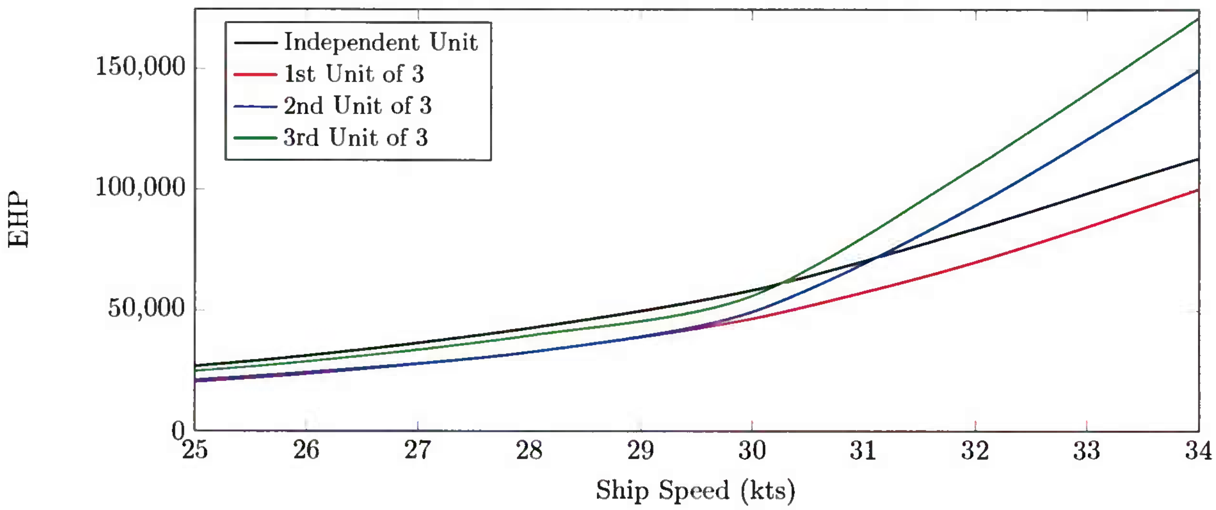



**(b) Heave**

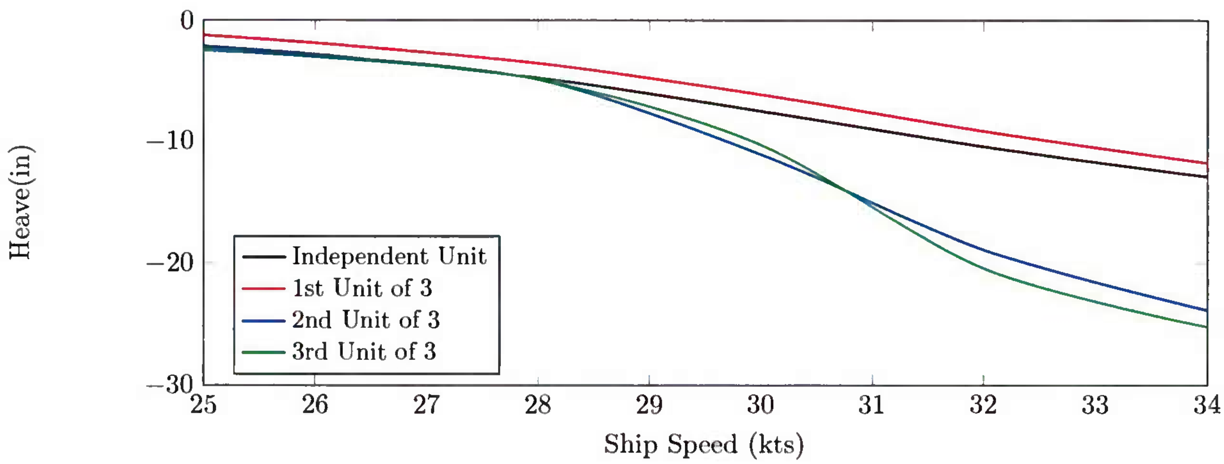



**(c) Pitch**

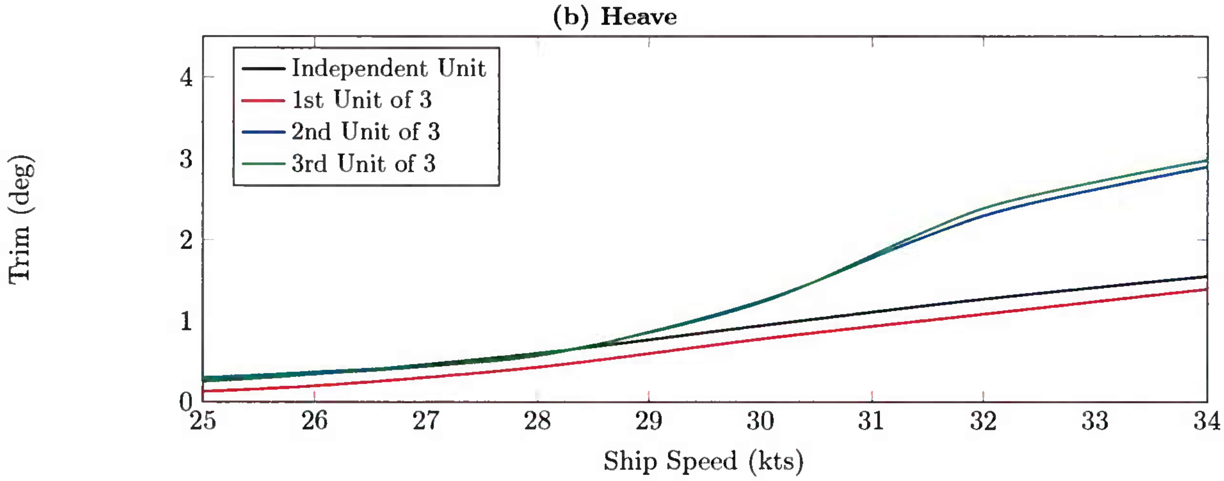
**Figure 20: Comparison of each unit in a 2 unit seatrain**




**(a) Effective Horsepower**

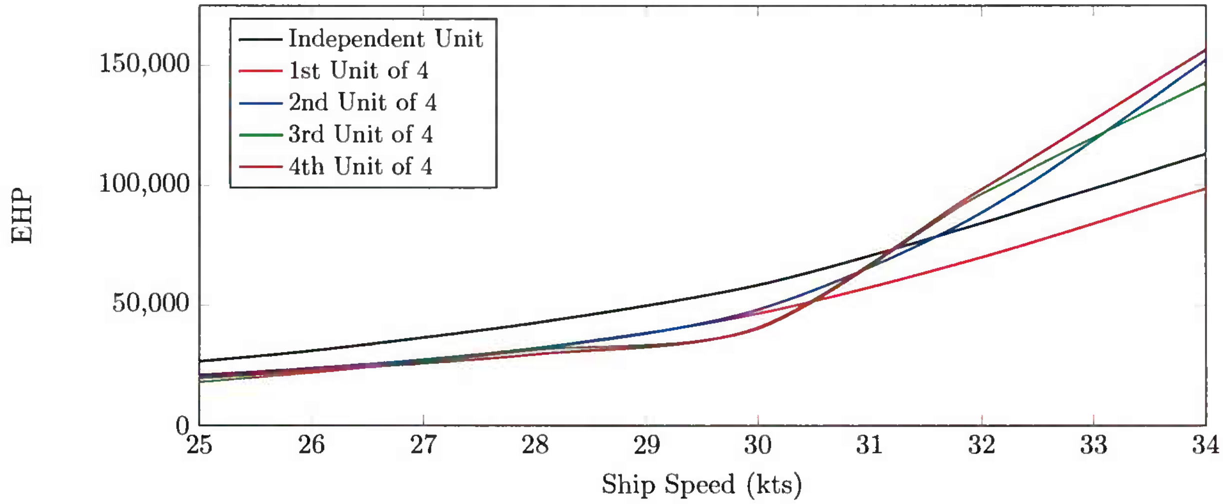



**(b) Heave**

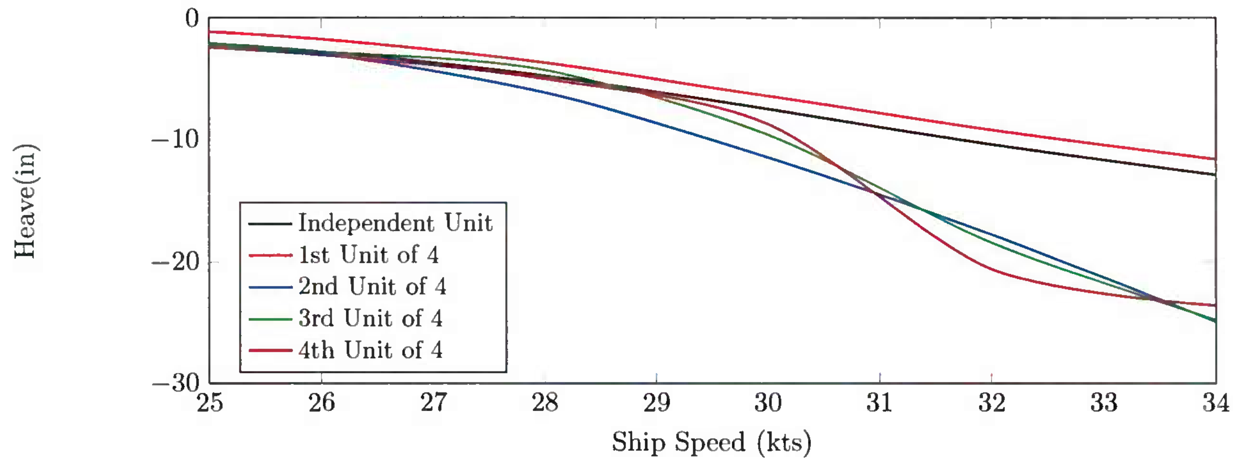



**(c) Pitch**

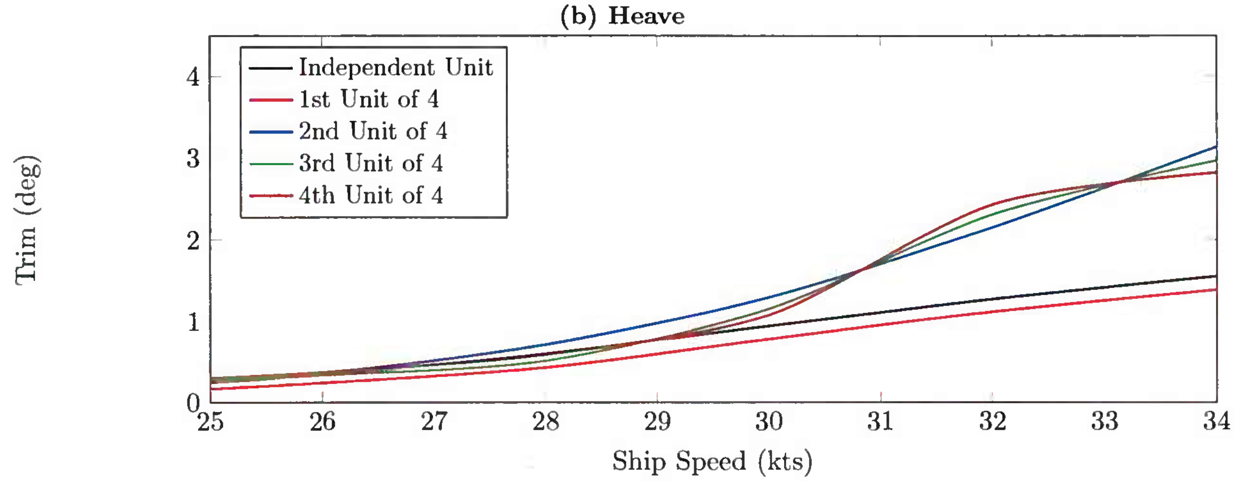
**Figure 21: Comparison of each unit in a 3 unit seatrain**




**(a) Effective Horsepower**




**(b) Heave**




**(c) Pitch**

**Figure 22: Comparison of each unit in a 4 unit seatrain**

**Figure 23: Pitching of second vehicle in a seatrain**

*Longitudinal Flow Through The Propeller Plane*

The rpm of single model propeller free-wheeling was measured on one model (positioned first, second, third, and fourth respectively in the seatrain). In the initial tests, all other shafts were outfitted with bare propeller hubs as in the resistance tests. The speed of the free-wheeling propeller provided the means to determine the effect on the flow velocity near the propeller without propeller wash. This method assumed that the propeller RPM would be linear with increasing speed. Figure 24 illustrates the free-wheeling propeller rpm for an independent unit as a function of speed.

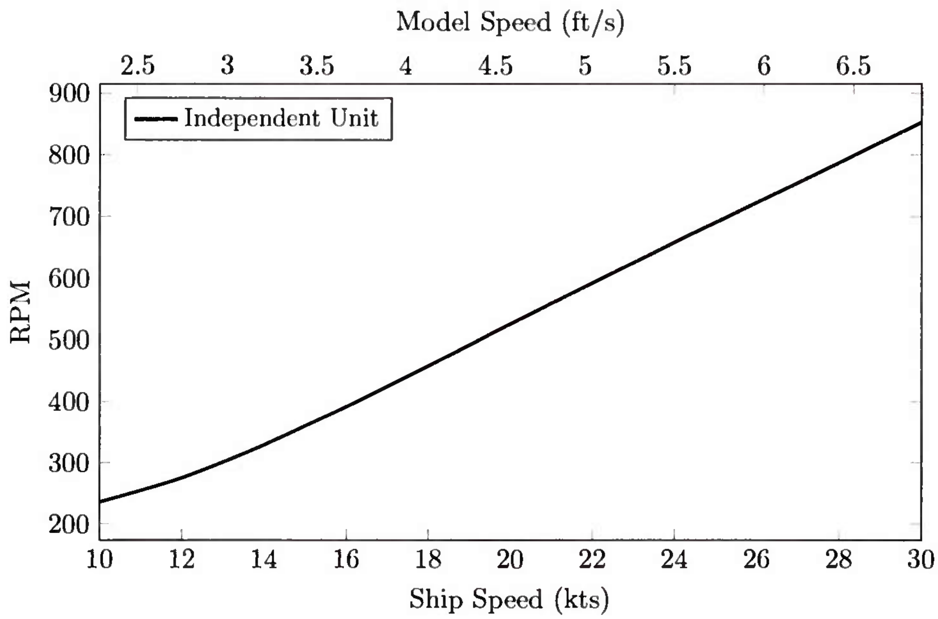
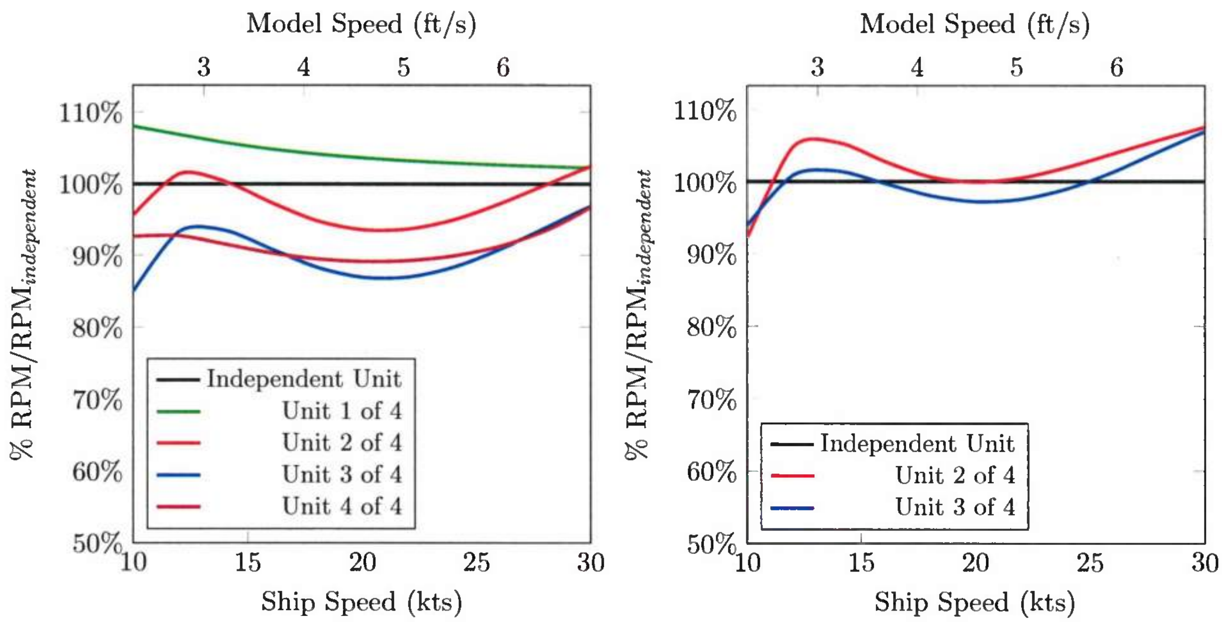



**Figure 24: Free-wheeling propeller RPM of an independent unit**

The free wheeling rpms obtained for the following units were compared against an independently running seatrain unit (Figure 25a). It can be seen that the farther back in the train the unit was, the more the inflow velocity was reduced until a limit is reached after the third model.

The same comparison was then run again with propellers operating on the ahead units to assess the impact of propeller wash. Time allowed for only the rpm of 2nd and then the 3rd unit to be measured when the forward units were powered to the model self-propulsion point. These were again normalized against an independent unit (Figure 25b). These results indicated that the propeller wash tended to offset the wake decrease of the forward hulls, and the following unit propellers see no significant change in the longitudinal flow through the propeller plane relative to an independently operating unit. This allows for identical unit design regardless of their position in the train. A full listing of all results can be found in Appendix D.




**(a) No propeller wash** **(b) Powered propeller wash**

**Figure 25: Free-wheeling RPM as a percentage of independent unit RPM**

### *Body Forces & Moments*

The unit forces can be found in Appendix E; they are to be used by CSC for the development/verification of a turning control algorithm.

## Tridelphia Reservoir Operational Demonstration Results

As this was purely a demonstration to show that the seatrain can be steered, many of the characteristics are expressed in model-scale units. The model mass distribution and rudder rates were similar to that of a typical ship in order to create a reasonable comparison point. The test was successful overall in that the model successfully executed various turns. Figure 26 shows an example of a turning maneuver where at 15 seconds the forward most rudder is turned to the full 30 degrees and maintained for greater than 100 seconds to generate the circle shown. The tracks shown are located where the gps

was on the forward most unit and on the equivalent position for the following units. At the beginning of the maneuver, as expected, the turning diameter of the forward most unit is the smallest and the aft unit has the largest turning diameter. Once steady state is reached in the turn, the seatrain conforms to the circle and the unit's respective radii become closer.

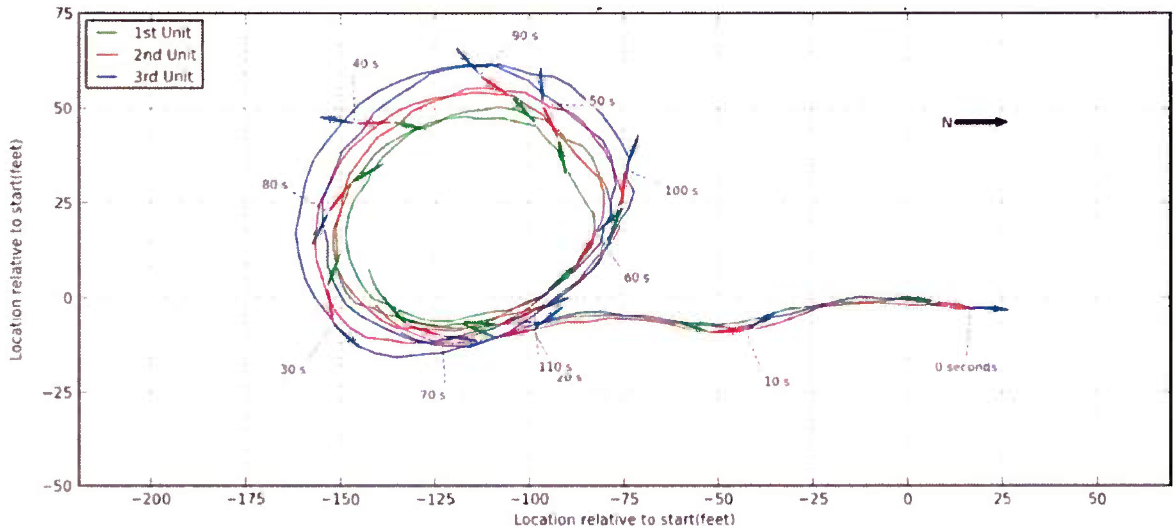



**Figure 26: Turning circle of three unit seatrain**

In Figure 27 the time period from approximately 60 seconds is an attempted straight line path and the time before 60 seconds is a 180 degree turn.

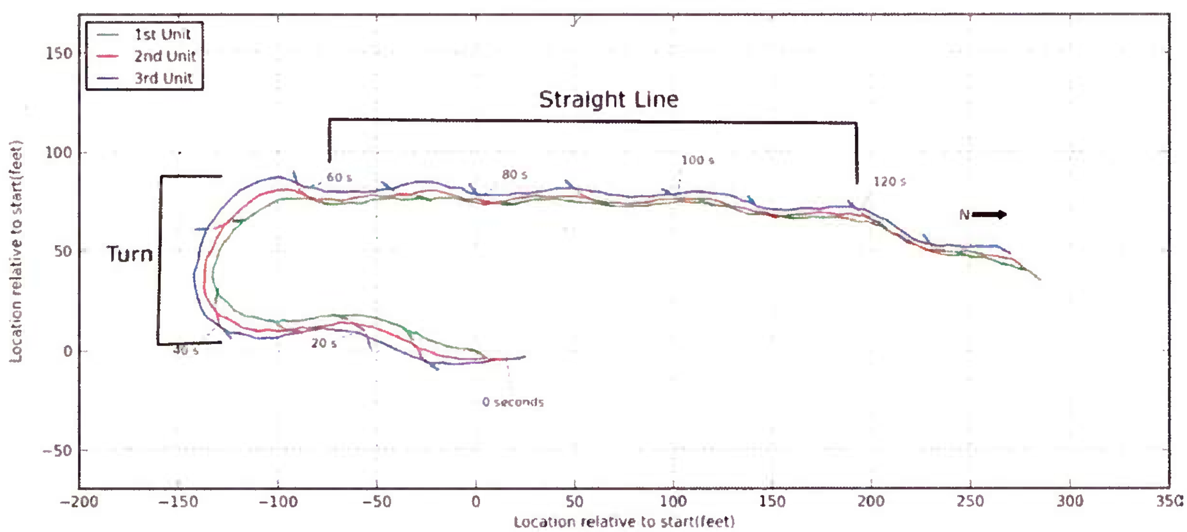
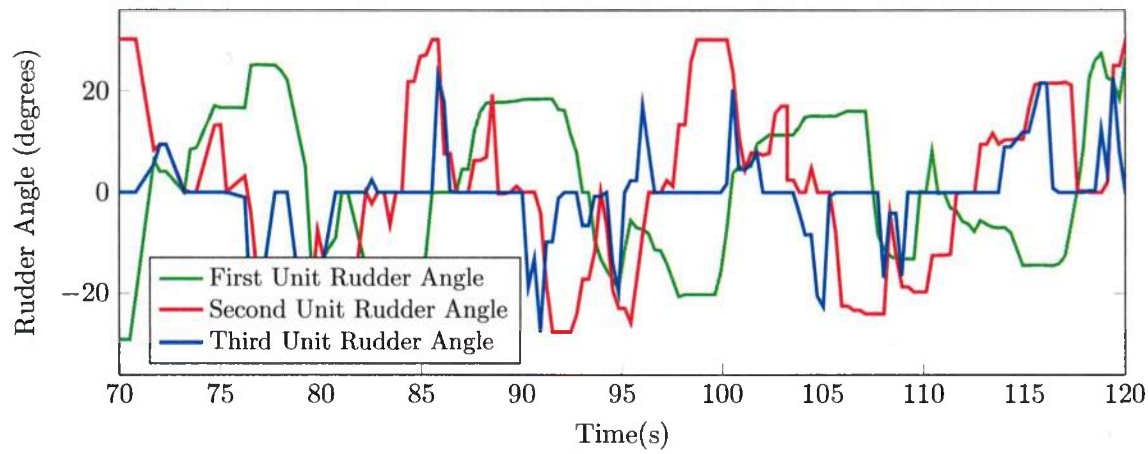


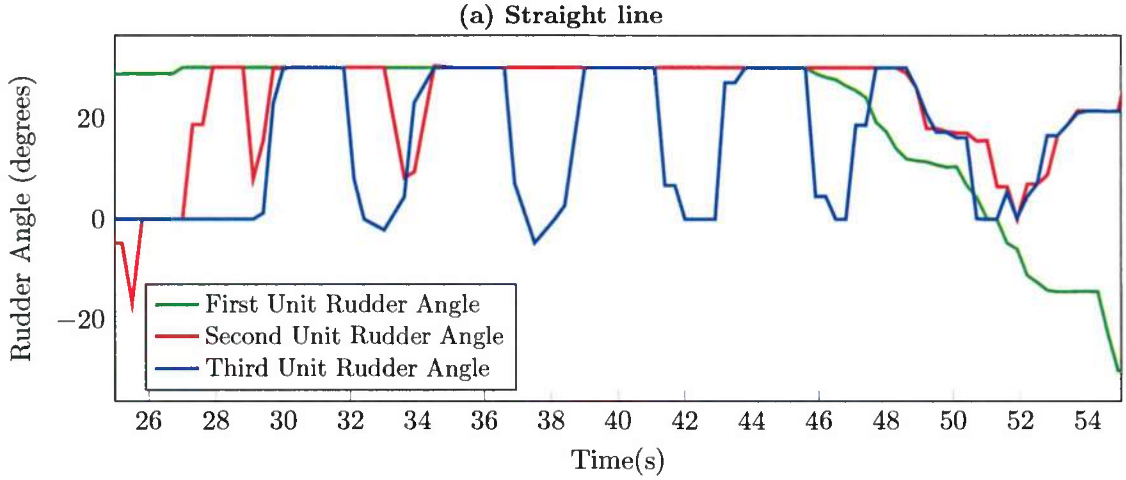

**Figure 27:** 180° **Turn execute of three unit seatrain**

The rudder data plotted in Figure 28 for these two sections of the maneuver show the difficulties that the user and the control algorithm had with controlling the aft units. Figure 28a illustrates the rudder activity during the straight line portion of the run. During the straight line the operator was

required to constantly control the unit in order to maintain the path. The operator's input is shown in Figure 28a and the course plotted in Figure 27 show the large lateral deviations from a desired straight line course associated with a typical hull. During the turn in figure 28b the first unit is given a constant rudder angle and the aft two units operate by switching between nearly zero and max rudder angle.



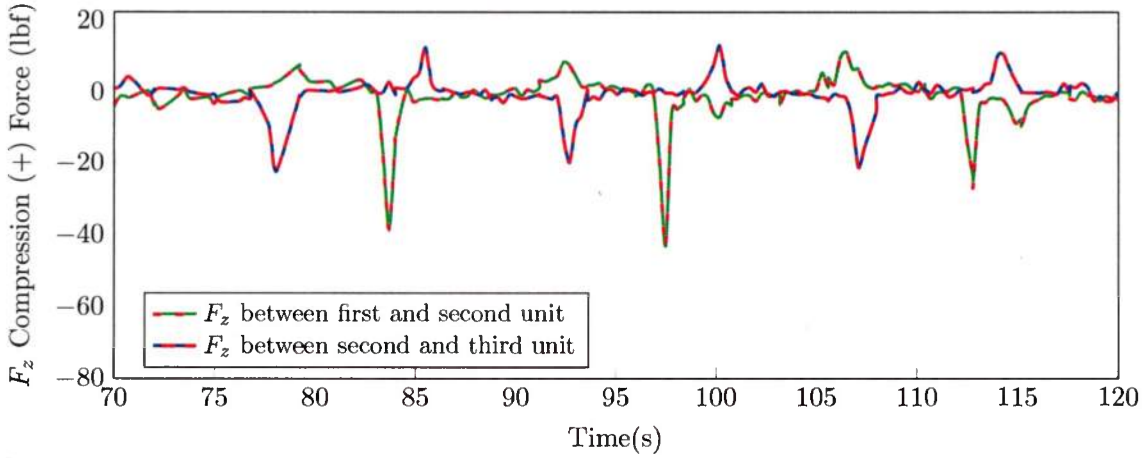

**(a) Straight line**



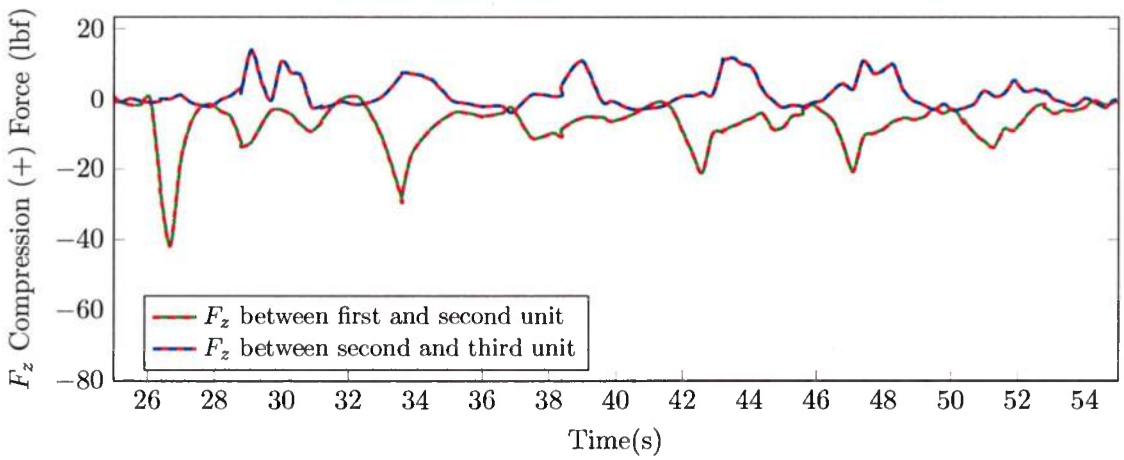

**(b) Turn**

**Figure 28: Rudder angle of units during a 180° turn execute of a three unit seatrain**

For the straight line path and the turn the $F_z$ or axial force between the models averages to zero over time (Figures 29a and 29b) indicating that each unit is able to operate under its own propulsion. The spikes of compression and tension between the models are due to the lateral oscillations in the vessels and mechanical delays. The full results with all forces and moments can be found in Appendix F.




**(a) Straight line**




**(b) Turn**

**Figure 29: Surge force between units during a 180° turn execute of a three unit seatrain**

# DISCUSSION

## Hydrodynamics

The original NSWCCD connectorless seatrain concept [Reference 3] saw improvements of up to 70% reduction in the resistance percent for a four unit seatrain. This result can be partially attributed to the inset V transom of the units but not entirely. It is the belief that thc scction area continuity along the length of the train accounts for a significant portion of the performance benefit. The original connectorless concept [Reference 3] total scction area continuity remains relatively consistent along the length compared to the HST seatrain (Figure 5). With improved fairing and design it may be possible to maintain more of the section area across the interface between units. The much more slender HST center hull ($L/B \approx 13$ for HST vs $L/B = 5$ for the connector-less) may also see less improvement than the connector-less for adding on units due to diminishing returns in reducing the

wave resistance. The outer hulls see little-to-no frictional benefits from being in a seatrain as there is little to no boundary layer transition between subsequent outriggers, due to the large longitudinal distance between outriggers of two adjacent seatrain units. Unpropelled testing illustrates a wake deficit however; the propeller wash has been shown to offset the reduced velocities.

### Operational Demonstration

Overall the model(s) were able to execute various maneuvers and exemplified the capabilities of the system. The units were difficult to manually steer in a straight line and operate in the water due to an unforeseen issue in the limitations of the linkage design and the large distance between the operator on the shore and the units. Once a relative yaw angle between two units reached a maximum, the sway force changed dramatically and the algorithm attempted to overcompensate by reversing the rudder creating large lateral oscillations. Designing a new gimbal and interface to allow for wider range relative yaw angles and an improved control system for each model (computationally and physically), could allow for a more robust and easier to control train. It may be possible that with further iterations, uncoupled seatrains can be designed. The current model testing experience emphasizes the importance of designing a robust steering control system.

## CONCLUSION

The seatrain designed herein had been specifically designed to allow yaw articulation between the units. The radio controlled seatrain model operated under shore side manual steering and speed control of the forward unit, with the secondary and tertiary units operated through feedback control algorithm. The train was able to execute multiple turning maneuvers. The maximum turning diameter was found to be three times the length of the assembled seatrain.

Controlling the three unit seatrain was difficult due to the simple nature of the following unit control algorithms and linkage design. A typical desired straight course had larger lateral deviations than associated with the operation of a typical monohull ship. The straight line course was difficult to maintain by the operator. The development of a better linkage design and automated control algorithm is necessary for a successful design.

All seatrain combinations of 2, 3, and 4 units reduced the resistance of the units for speeds up to and including a speed of 30 knots. Lack of reduction at speeds above 30 knots may be associated with the trim of the vessels rapidly increasing at these speeds. The resistance reduction per unit increased with the number of units. The four unit seatrain had a resistance reduction per unit of 24% to 30% in the 10 to 30 knot speed range.

It is desired to have identical units in a seatrain, including identical propellers, in order to allow any unit to assume any position within the train. The propeller average longitudinal inflow velocity variation as a function of position in the seatrain was briefly investigated by the use of a freewheeling propeller. Based on the results it appears that the inflow velocities change by no more than 10% from unit to unit, and such a variation should be easily accommodated efficiently by controllable pitch propellers.

Total body forces and connecting forces and moments between units were measured on a rigidly held three unit seatrain tested in the linear tow basin. The leading and trailing seatrain units were deflected in yaw to prescribed small angles. The forces were measured to aid the assembly of a future maneuvering simulation code.

This page intentionally left blank.

# REFERENCES


[1] *America's Marine Highway Program.* Department of Transportation. 2011. URL: http://www.marad.dot.gov/ships_shipping_landing_page/mhi_home/mhi_home.htm.

[2] *Improved Navy Lighterage System.* Accessed: 1/17/2013. Global Security. URL: http://www.globalsecurity.org/military/systems/ship/inls.htm.

[3] Gabor Karafiath, Bryson Metcalf, and Jesse Geisbert. "Seatrain for High Capacity, High Speed, Ocean Transport". In: FAST. Athens, Greece, Oct. 2009.

[4] *Mobile Offshore Base.* Accessed: 1/17/2013. Global Security. URL: http://www.globalsecurity.org/military/systems/ship/mob.htm.

This page intentionally left blank.

# APPENDIX A: SEATRAIN SHEAR LAYER SCALING ANALYSIS

The total resistance ($R_T$) of a ship or model can be characterized by two components, residuary ($R_R$) and frictional resistance ($R_F$). The total resistance and its components are typically utilized in their coefficient form. The total ($C_T$), residuary ($C_R$) and frictional ($C_F$) resistance coefficients are determined by normalizing the individual resistance forces with a combination of water density, water speed, and the wetted surface area.

$$\begin{aligned} C_T &= C_R + C_F \\ \frac{R_T}{\frac{\rho}{2}V^2 S} &= \frac{R_R}{\frac{\rho}{2}V^2 S} + \frac{R_F}{\frac{\rho}{2}V^2 S} \end{aligned} \tag{A1}$$

When scaling from model-scale to full-scale the coefficients only equate at certain relative speeds. For the coefficient of residuary resistance to equate from model to full-scale the ships have to be run at an equivalent Froude number.

$$F_n = \frac{V_s}{\sqrt{gL_s}} = \frac{V_m}{\sqrt{gL_m}} \tag{A2}$$

Froude scaled speeds allow the units to be run at velocities that are a function of the inverse of the square root of the scale ratio ($L_s/L_m$) and speed. Under froude scaling the ship and model's coefficient of friction is defined using the ITTC 1957 ship-model correlation line (A3).

$$C_F = \frac{0.075}{(log_{10}R_N - 2)^2} \tag{A3}$$

Based on experience with surface ships a Correlation Allowance Coefficient ($C_A$) is added to the frictional portion of resistance. This number is often predetermined by correlations of model and full-scale data and typically ranges from 0.0000 to 0.0005. For the purposes of this test a $C_A$ of 0.000 is used.

## Resistance Scaling

For a single hull the equation for determining the coefficient of total resistance for full scale is given below.

$$C_{Tship} = C_{Tmodel} - C_{Fmodel} + C_{Fship} + C_A \tag{A4}$$

The method for determining the friction on a seatrain is slightly more complex than a single hull due to the development of the shear layer from hull to hull. By having the hulls in such close proximity the shear layer will grow over the entire length as if the entire train was one hull. This also causes the shear layer to affect each model's individual value of skin friction differently. Figure A-1 below visually explains this discussion.

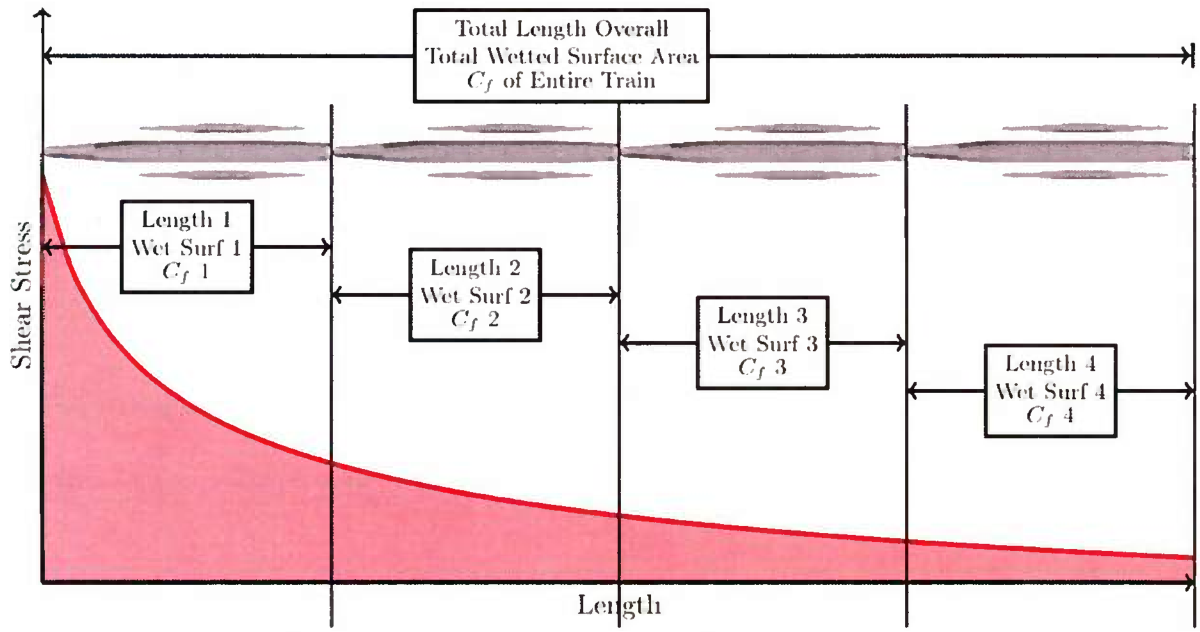



**Figure A-1: Shear layer growth over a seatrain**

This means the individual friction of each ship can be expressed as the integration of the overall friction across the train. Since each ship has the same velocity as the overall train the friction can be normalized by the dynamic head. This creates an integral that can be approximated with the following summation.

$$\frac{R_{Fcenter}}{\frac{\rho}{2}V^2} = \frac{0.0075\sum_{n=1}^{m}\{S_n\}}{\left[log_{10}\left(\frac{\rho V\sum_{n=1}^{m}\{L_n\}}{\mu}\right)-2\right]^2} - \frac{0.0075\sum_{n=1}^{m-1}\{S_n\}}{\left[log_{10}\left(\frac{\rho V\sum_{n=1}^{m-1}\{L_n\}}{\mu}\right)-2\right]^2} \tag{A5}$$

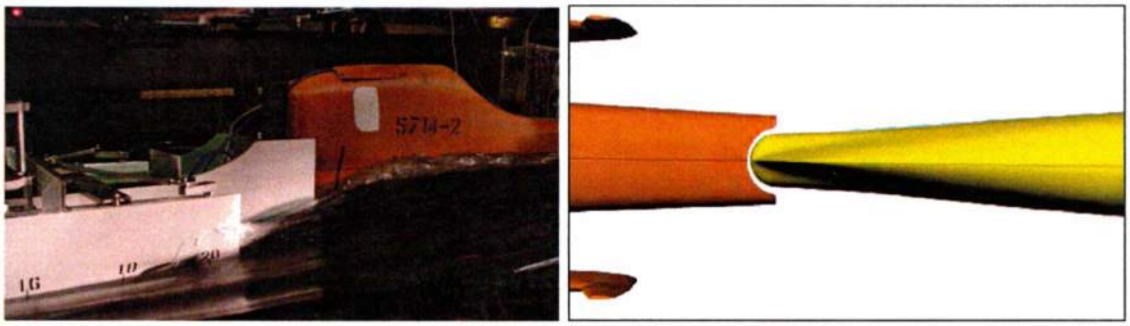
$R_{Fcenter}$ = Resistance of center Hull

$m$ = Number of unit being examined

$S_n$ = Surface Area of Unit n

$L_n$ = Length of Unit n

Due to the interface between hulls the equation becomes decidedly more complex and a factor for estimating this effect has to be included. Due to this interface (Figure A-2) between hulls the overall length of the train is less than determined by simply adding up individual lengths of hull. The percentage overlap of each overlap section can be also expressed as the surface area of the length of the overlap of one vessel divided by the surface area of both along the length of the overlap. The equation for this ratio is below.



(a) Carriage Test (b) 3D Model

**Figure A-2: Overlap of bow and stern sections**

$$
\begin{aligned}
Rat_{aft} &= \frac{\text{Wetted Surface Area of the Aft Unit's Interface Section}}{\text{Total Wetted Surface Area of Both Units' Interface Section}} \\
Rat_{fwd} &= \frac{\text{Wetted Surface Area of the Forward Unit's Interface Section}}{\text{Total Wetted Surface Area of Both Units' Interface Section}}
\end{aligned}
\tag{A6}
$$

The equation for each model becomes complex so a more simple nomenclature system was adopted.

$$
\begin{aligned}
&LOA_n = \text{Total length of train up to the aft section of of model } n \\
&L_n = LOA_n - \text{the length of interface} \\
&SOA_n = \text{Total Surface area of the train along the section that } LOA_n \text{ denotes} \\
&S_n = \text{Total Surface area of the train along the section that } L_n \text{ denotes}
\end{aligned}
\tag{A7}
$$

The equation for friction of the center hulls follows.

$$
\begin{aligned}
\frac{R_{Fcenter}}{\frac{\rho}{2}V^2} = \\
& \frac{0.0075 S_m}{\left[log_{10}\left(\frac{\rho V L_m}{\mu}\right)-2\right]^2} \\
& +Rat_{fwd}\left\{\frac{0.0075 SOA_m}{\left[log_{10}\left(\frac{\rho V LOA_m}{\mu}\right)-2\right]^2}-\frac{0.0075 S_m}{\left[log_{10}\left(\frac{\rho V L_m}{\mu}\right)-2\right]^2}\right\} \\
- & \frac{0.0075 S_{m-1}}{\left[log_{10}\left(\frac{\rho V LOA_{m-1}}{\mu}\right)-2\right]^2} \\
& +Rat_{aft}\left\{\frac{0.0075 SOA_{m-1}}{\left[log_{10}\left(\frac{\rho V LOA_{m-1}}{\mu}\right)-2\right]^2}-\frac{0.0075 S_{m-1}}{\left[log_{10}\left(\frac{\rho V L_{m-1}}{\mu}\right)-2\right]^2}\right\} \\
m = & \text{ Number of unit being examined}
\end{aligned} \tag{A8}
$$

Since the train is also a trimaran the equation above only applies to the center hull. This means that the frictional resistance of the side hulls also need to be separately calculated. It is assumed that the side hulls are small enough to exist outside the boundary layer effects of the other hulls except for marginally reduced flow rate the farther back in the train they are. The frictional resistance for one side hull is below, this can then be multiplied by two.

$$
\begin{aligned}
\frac{R_{Fside}}{\frac{\rho}{2}V^2} &= \frac{0.0075 S_{mside}}{\left[log_{10}\left(\frac{\rho \alpha V L_{mside}}{\mu}\right)-2\right]^2} \\
\alpha &\approx 1
\end{aligned} \tag{A9}
$$

The term $\alpha$ decreases the further aft one is in the seatrain. For this set of tests the order of 1, 0.99, 0.98, 0.96 was used from the freewheeling propeller test for the first, second, third and fourth units' side hulls respectively.

This page intentionally left blank.

# APPENDIX B: TOTAL SEATRAIN RESISTANCE DATA

## One Unit, 0° Static Trim, Side Hulls Middle, Test 1

$\lambda = 54.134$ $\quad T = 19.5$ feet

$\Delta = 10628$ LT $\quad LOA = 541.3$ feet

**Table B-1: One unit, 0° static trim, side hulls middle, test 1, resistance data**

| SPEED [kts] | EHP [hp] | $C_R$ $10^3$ | L/D | TF | $C_F$ $10^3$ |
|---|---|---|---|---|---|
| 10 | 1,244 | 0.87 | 587 | 411 | 1.67 |
| 12 | 2,373 | 1.18 | 369 | 259 | 1.63 |
| 14 | 3,722 | 1.17 | 275 | 192 | 1.6 |
| 16 | 5,739 | 1.29 | 204 | 143 | 1.57 |
| 18 | 9,374 | 1.74 | 140 | 98 | 1.55 |
| 20 | 12,045 | 1.55 | 121 | 85 | 1.53 |
| 22 | 16,601 | 1.67 | 97 | 68 | 1.51 |
| 24 | 22,956 | 1.9 | 76 | 53 | 1.49 |
| 26 | 31,178 | 2.14 | 61 | 43 | 1.48 |
| 28 | 42,758 | 2.51 | 48 | 33 | 1.46 |
| 30 | 58,537 | 2.97 | 37 | 26 | 1.45 |
| 32 | 84,158 | 3.8 | 28 | 19 | 1.44 |
| 34 | 113,137 | 4.45 | 22 | 15 | 1.43 |
| 36 | 139,032 | 4.66 | 19 | 13 | 1.42 |
| 38 | 163,105 | 4.66 | 17 | 12 | 1.41 |
| 40 | 187,927 | 4.59 | 16 | 11 | 1.4 |

*TF is transport factor assuming a 0.7 propulsive efficiency

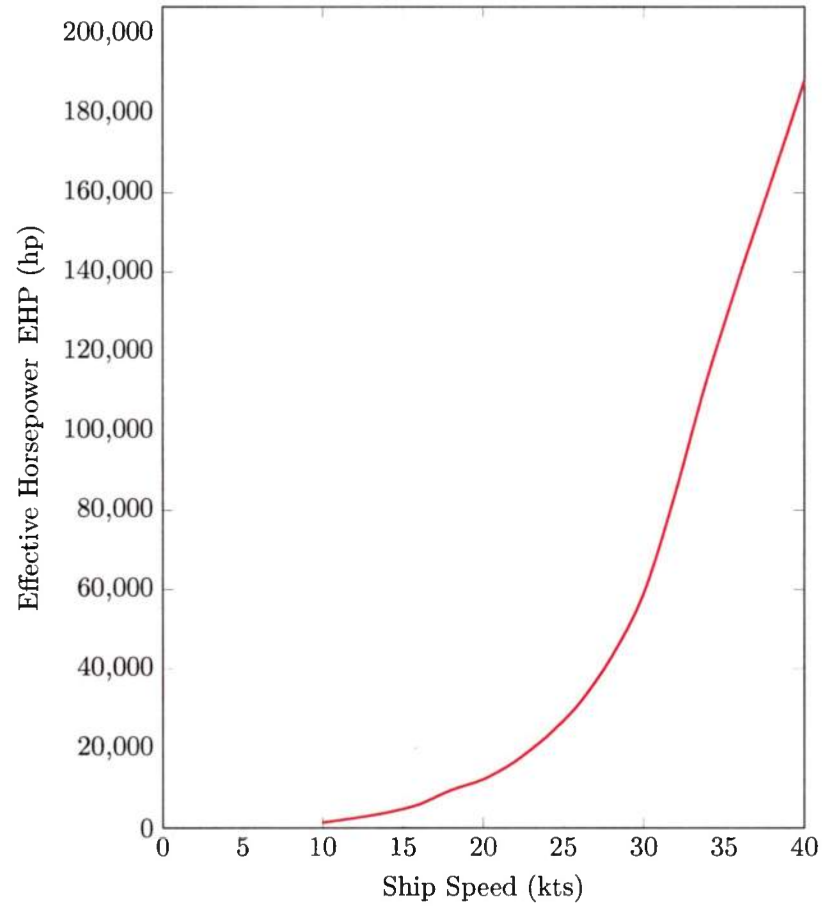



**Figure B-1: One unit, 0° static trim, side hulls middle, test 1, total resistance**

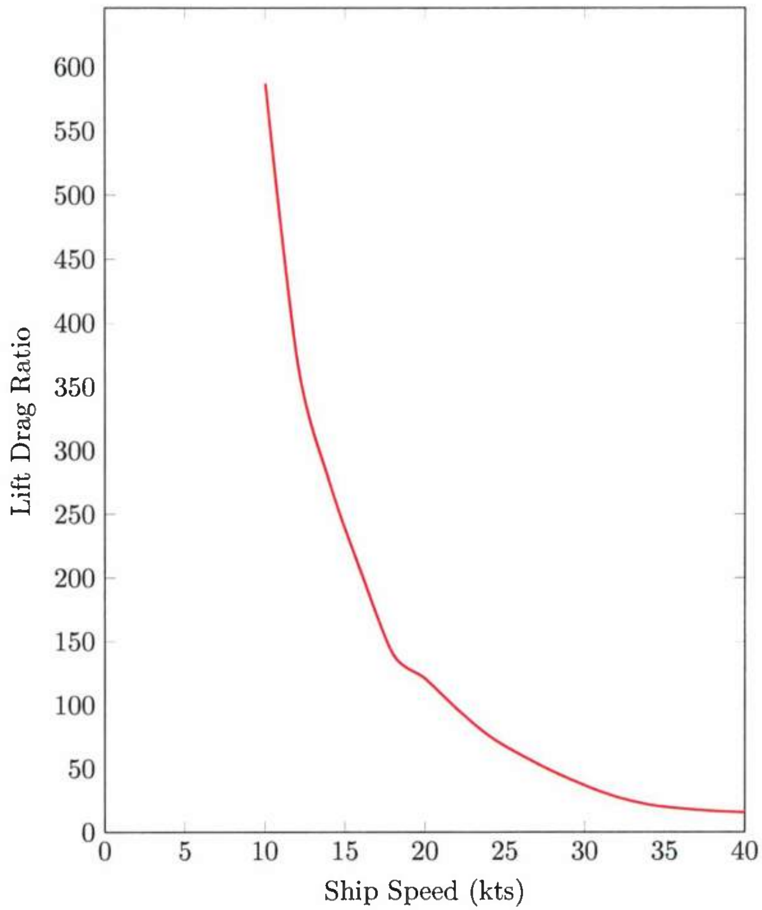



**Figure B-2: One unit, 0° static trim, side hulls middle, test 1, lift drag ratio**

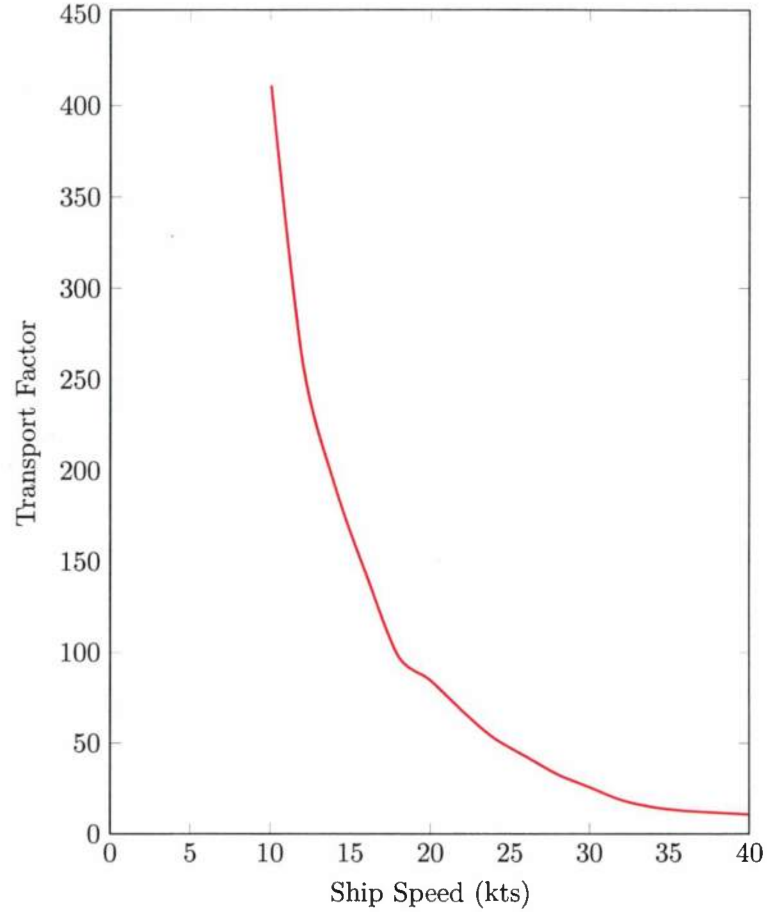



**Figure B-3: One unit, 0° static trim, side hulls middle, test 1, transport factor**

## One Unit, $-1°$ Static Trim, Side Hulls Middle, test 2

$\lambda = 54.134$ $\quad T = 19.5$ feet

$\Delta = 10628$ LT $\quad LOA = 541.3$ feet

**Table B-2: One unit, $-1°$ static trim, side hulls middle, test 2, resistance data**

| SPEED [kts] | EHP [hp] | $C_R$ $10^3$ | L/D | TF | $C_F$ $10^3$ |
|---|---|---|---|---|---|
| 10 | 1,330 | 1.05 | 1,101 | 771 | 1.67 |
| 12 | 3,949 | 3.04 | 445 | 311 | 1.63 |
| 14 | 6,329 | 3.11 | 324 | 227 | 1.6 |
| 16 | 10,265 | 3.55 | 228 | 160 | 1.57 |
| 18 | 15,480 | 3.87 | 170 | 119 | 1.55 |
| 20 | 20,822 | 3.79 | 141 | 98 | 1.53 |
| 22 | 27,049 | 3.68 | 119 | 83 | 1.51 |
| 24 | 35,743 | 3.79 | 98 | 69 | 1.49 |
| 26 | 48,144 | 4.11 | 79 | 55 | 1.48 |
| 28 | 66,605 | 4.73 | 62 | 43 | 1.46 |
| 30 | 90,105 | 5.36 | 49 | 34 | 1.45 |
| 32 | 123,287 | 6.24 | 38 | 27 | 1.44 |
| 34 | 161,785 | 6.97 | 31 | 22 | 1.43 |
| 36 | 193,611 | 7.05 | 27 | 19 | 1.42 |
| 38 | 226,597 | 7.02 | 25 | 17 | 1.41 |
| 40 | 263,134 | 6.99 | 22 | 16 | 1.4 |

*TF is transport factor assuming a 0.7 propulsive efficiency

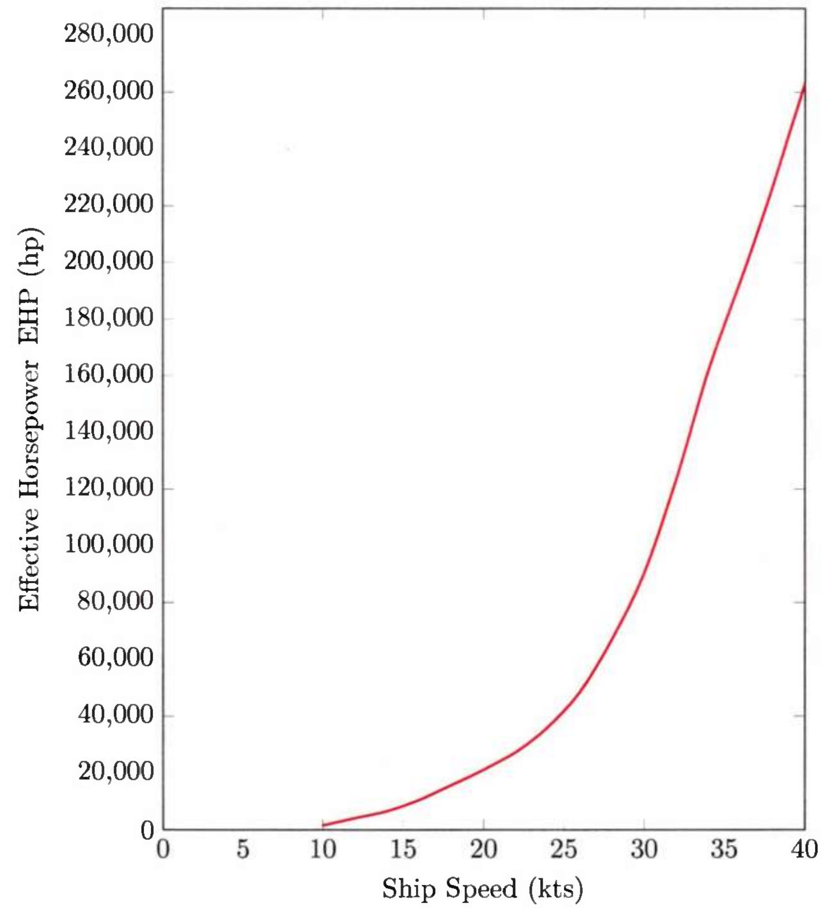



**Figure B-4: One unit, $-1°$ static trim, side hulls middle, test 2, total resistance**

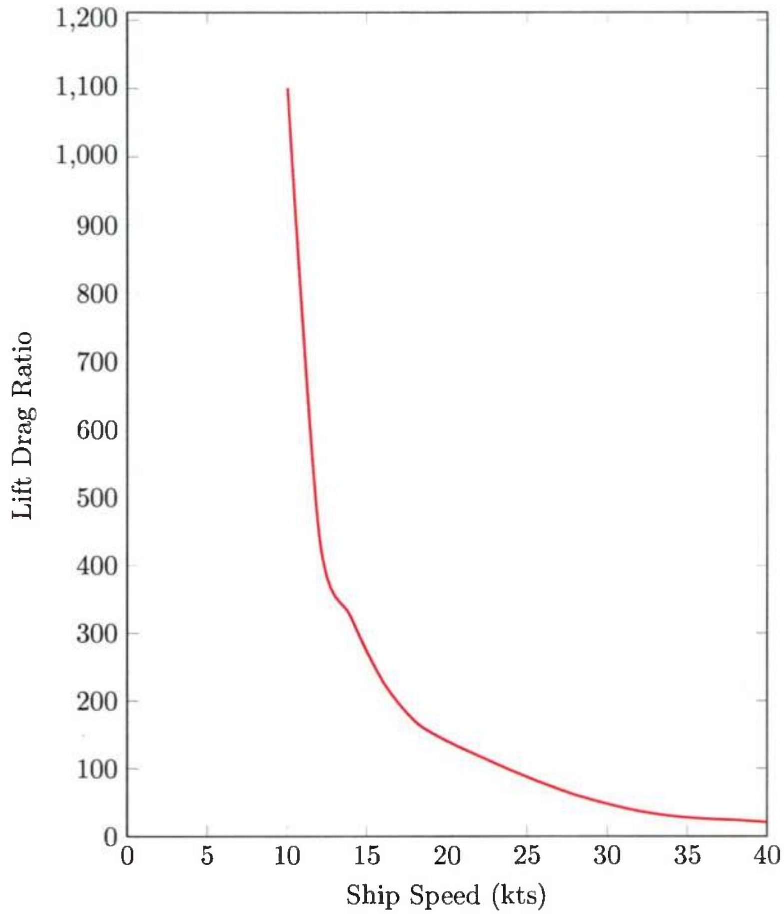



**Figure B-5: One unit, −1° static trim, side hulls middle, test 2, lift drag ratio**

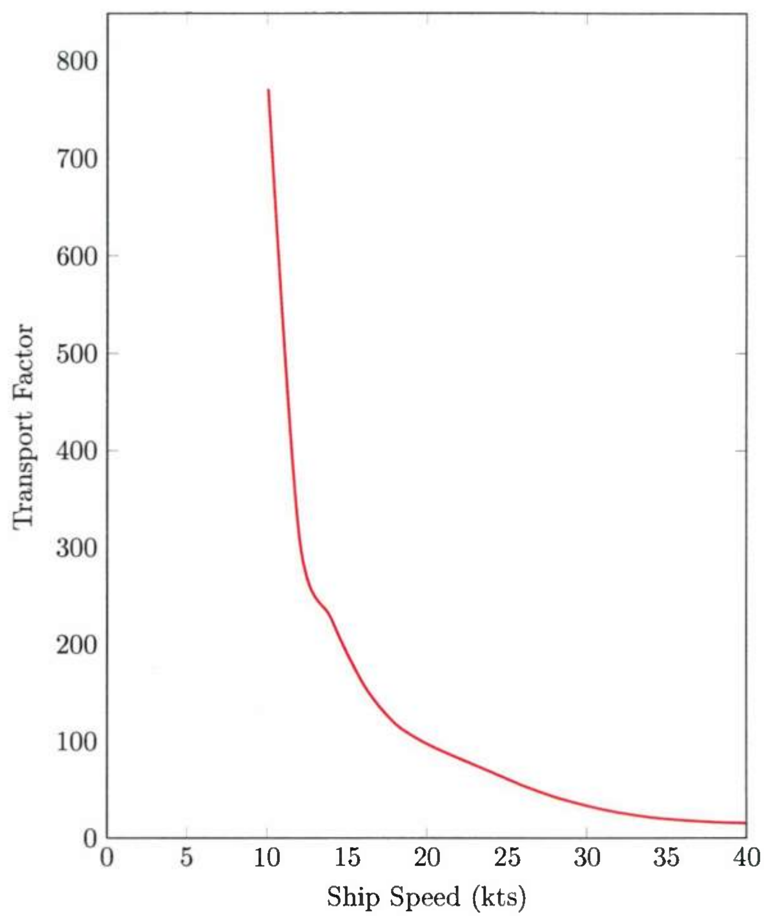



**Figure B-6: One unit, −1° static trim, side hulls middle, test 2, transport factor**

## One Unit, 0° Static Trim, Side Hulls Aft, Test 3

| | | | |
|---|---|---|---|
| $\lambda$ | $= 54.134$ | $T$ | $= 19.5$ feet |
| $\Delta$ | $= 10628$ LT | $LOA$ | $= 541.3$ feet |

**Table B-3: One unit, 0° static trim, side hulls aft, test 3, resistance data**

| SPEED [kts] | EHP [hp] | $C_R$ $10^3$ | L/D | TF | $C_F$ $10^3$ |
|---|---|---|---|---|---|
| 10 | 1,303 | 0.99 | 1,124 | 787 | 1.67 |
| 12 | 3,987 | 3.08 | 441 | 309 | 1.63 |
| 14 | 6,197 | 3.01 | 331 | 232 | 1.6 |
| 16 | 10,088 | 3.46 | 232 | 163 | 1.57 |
| 18 | 13,389 | 3.14 | 197 | 138 | 1.55 |
| 20 | 17,943 | 3.05 | 163 | 114 | 1.53 |
| 22 | 25,593 | 3.4 | 126 | 88 | 1.51 |
| 24 | 39,176 | 4.29 | 90 | 63 | 1.49 |
| 26 | 55,671 | 4.99 | 68 | 48 | 1.48 |
| 28 | 73,667 | 5.39 | 56 | 39 | 1.46 |
| 30 | 97,062 | 5.89 | 45 | 32 | 1.45 |
| 32 | 121,686 | 6.14 | 39 | 27 | 1.44 |
| 34 | 144,904 | 6.1 | 34 | 24 | 1.43 |
| 36 | 168,713 | 5.96 | 31 | 22 | 1.42 |
| 38 | 193,885 | 5.8 | 29 | 20 | 1.41 |
| 40 | 218,867 | 5.58 | 27 | 19 | 1.4 |

*TF is transport factor assuming a 0.7 propulsive efficiency

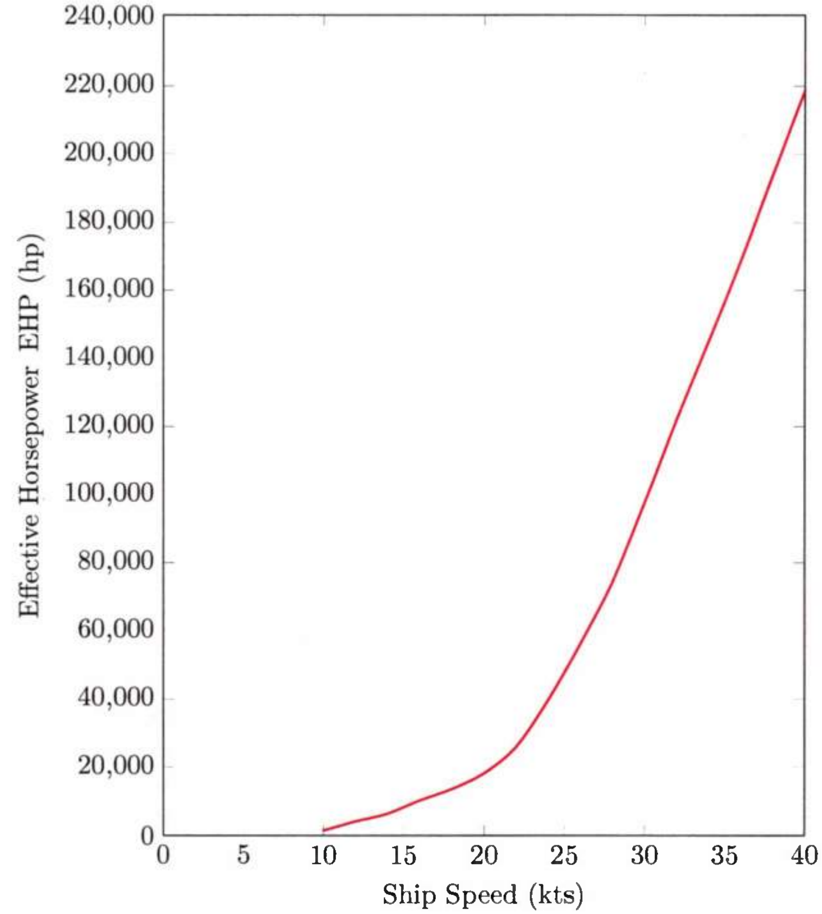



**Figure B-7: One unit, 0° static trim, side hulls aft, test 3, total resistance**

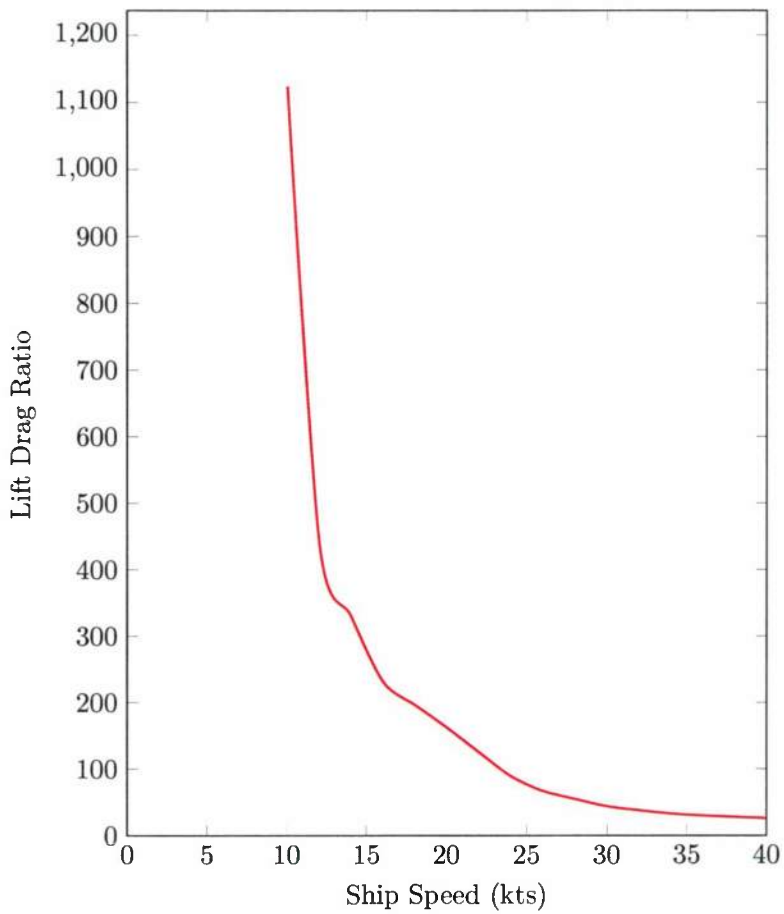



**Figure B-8: One unit, 0° static trim, side hulls aft, test 3, lift drag ratio**

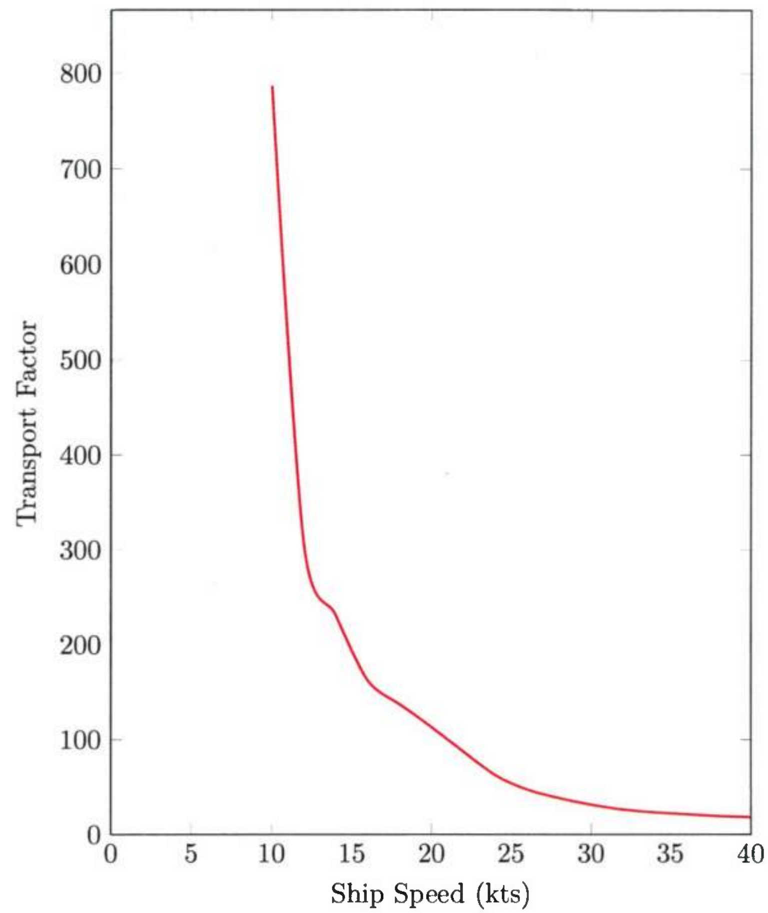



**Figure B-9: One unit, 0° static trim, side hulls aft, test 3, transport factor**

## Two Unit, 0° Static Trim, Test 4

$\lambda = 54.134 \qquad T = 19.5$ feet

$\Delta = 21257$ LT $\qquad LOA = 1072$ feet

**Table B-4: Two unit, 0° static trim, test 4, resistance data**

| SPEED [kts] | EHP [hp] | $C_R$ $10^3$ | L/D | TF | $C_F$ $10^3$ |
|---|---|---|---|---|---|
| 10 | 2,282 | 0.73 | 640 | 448 | 1.6 |
| 12 | 4,136 | 0.88 | 424 | 297 | 1.56 |
| 14 | 6,755 | 0.98 | 303 | 212 | 1.53 |
| 16 | 10,383 | 1.08 | 225 | 158 | 1.51 |
| 18 | 15,307 | 1.19 | 172 | 120 | 1.49 |
| 20 | 21,782 | 1.31 | 134 | 94 | 1.47 |
| 22 | 30,164 | 1.44 | 107 | 75 | 1.45 |
| 24 | 40,927 | 1.59 | 86 | 60 | 1.44 |
| 26 | 54,765 | 1.76 | 69 | 49 | 1.42 |
| 28 | 73,638 | 2.02 | 56 | 39 | 1.41 |
| 30 | 108,086 | 2.69 | 41 | 28 | 1.4 |
| 32 | 177,115 | 4.13 | 26 | 18 | 1.39 |
| 34 | 260,648 | 5.4 | 19 | 13 | 1.38 |
| 36 | 337,245 | 6.02 | 16 | 11 | 1.37 |
| 38 | 385,847 | 5.82 | 14 | 10 | 1.36 |

*TF is transport factor assuming a 0.7 propulsive efficiency

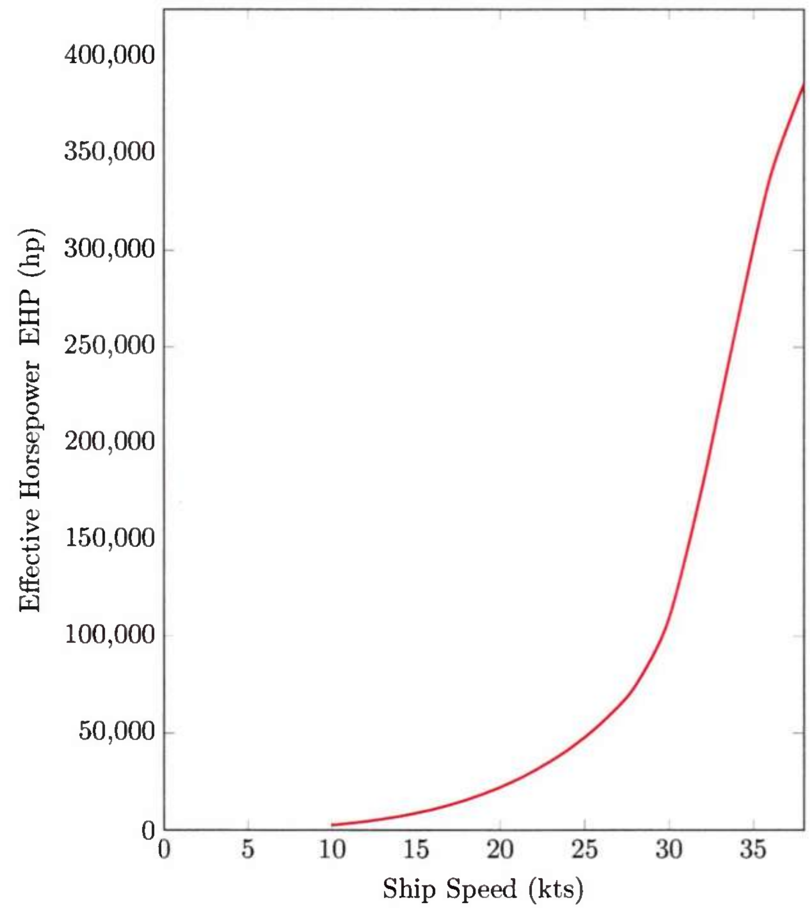



**Figure B-10: Two unit, 0° static trim, test 4, total resistance**

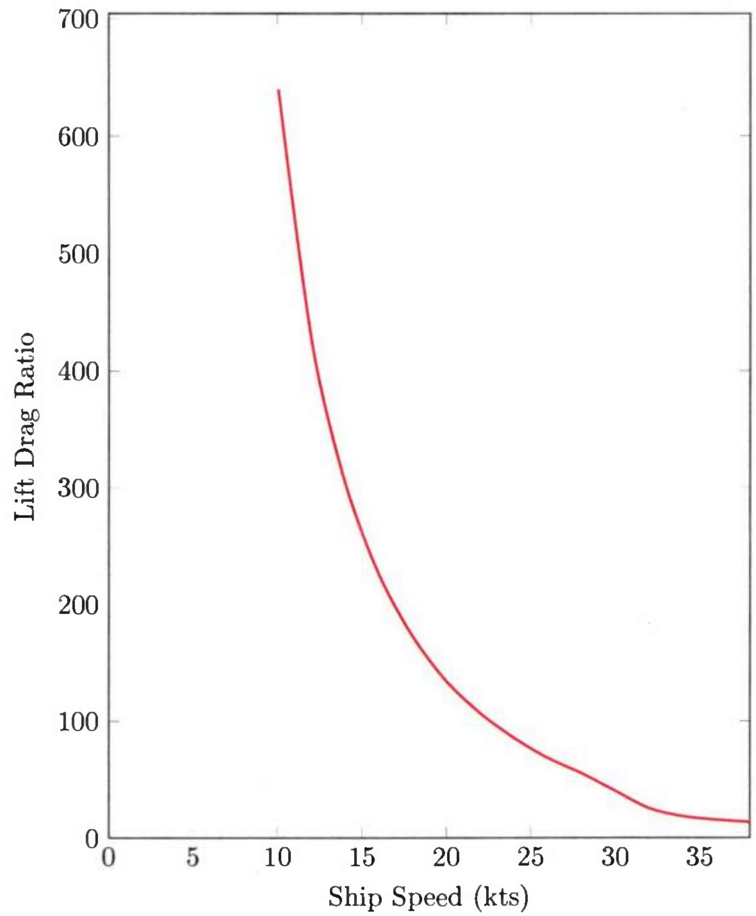



**Figure B-11: Two unit, 0° static trim, test 4, lift drag ratio**

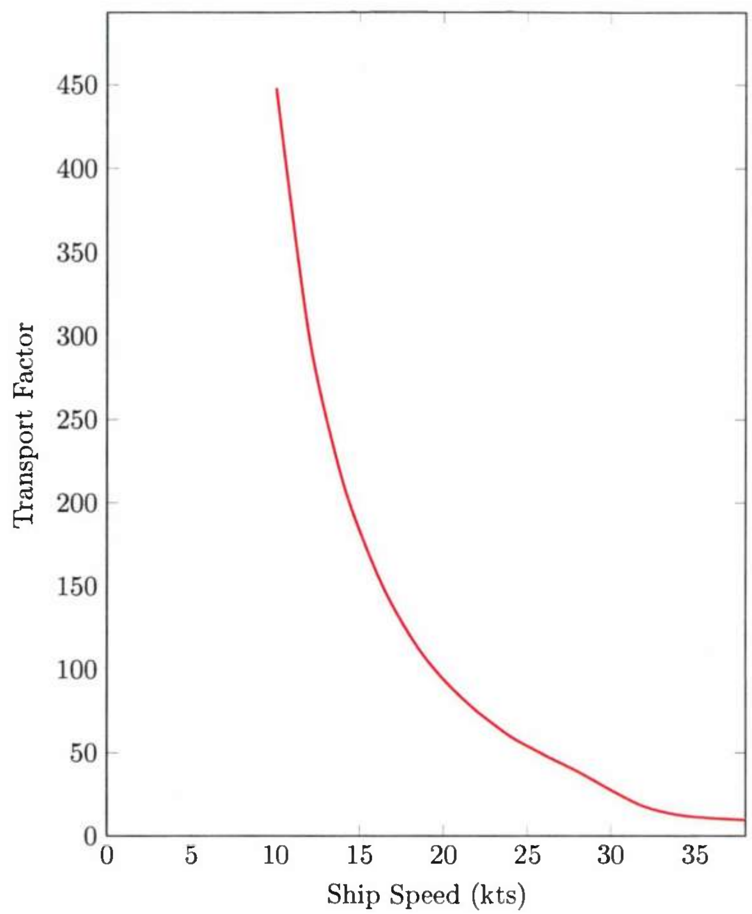



**Figure B-12: Two unit, 0° static trim, test 4, transport factor**

### Three Unit, 0° Static Trim, Test 5

$\lambda = 54.134 \quad T = 19.5$ feet

$\Delta = 31885$ LT $\quad LOA = 1603$ feet

**Table B-5: Three unit, 0° static trim, test 5, resistance data**

| SPEED [kts] | EHP [hp] | $C_R$ $10^3$ | L/D | TF | $C_F$ $10^3$ |
|---|---|---|---|---|---|
| 10 | 3,174 | 0.6 | 691 | 483 | 1.56 |
| 12 | 5,666 | 0.71 | 464 | 325 | 1.52 |
| 14 | 9,470 | 0.86 | 324 | 227 | 1.49 |
| 16 | 15,217 | 1.06 | 230 | 161 | 1.47 |
| 18 | 23,458 | 1.29 | 168 | 118 | 1.45 |
| 20 | 32,585 | 1.34 | 135 | 94 | 1.43 |
| 22 | 43,112 | 1.34 | 112 | 78 | 1.41 |
| 24 | 56,764 | 1.4 | 93 | 65 | 1.4 |
| 26 | 76,333 | 1.57 | 75 | 52 | 1.39 |
| 28 | 104,518 | 1.87 | 59 | 41 | 1.37 |
| 30 | 151,897 | 2.47 | 43 | 30 | 1.36 |
| 32 | 273,301 | 4.33 | 26 | 18 | 1.35 |
| 34 | 421,972 | 5.97 | 18 | 12 | 1.34 |

*TF is transport factor assuming a 0.7 propulsive efficiency

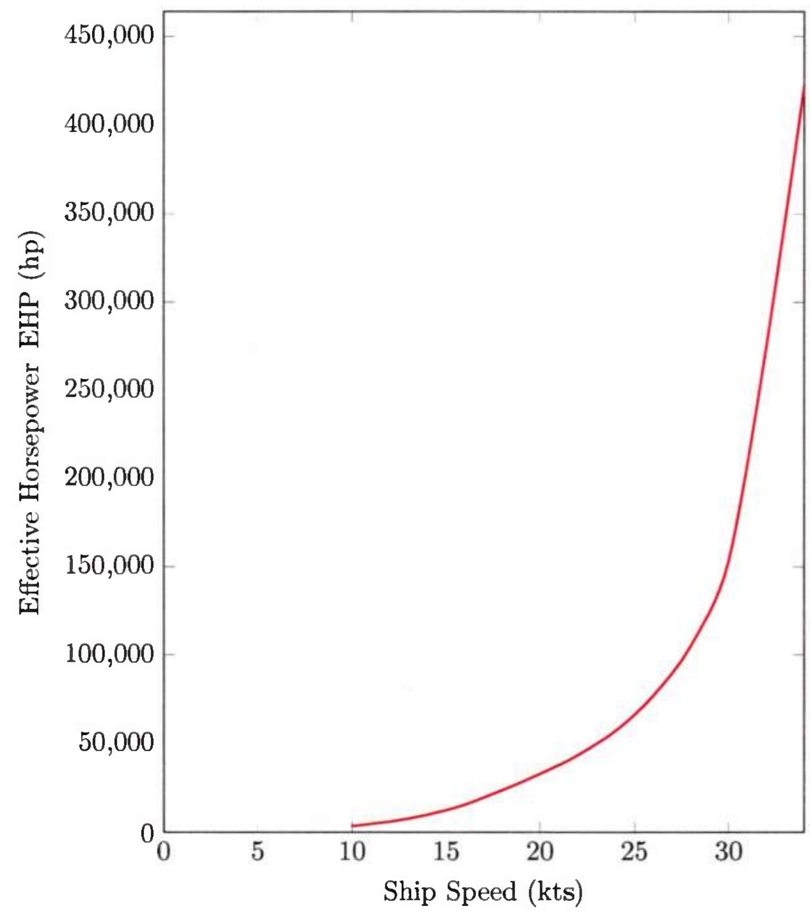



**Figure B-13: Three unit, 0° static trim, test 5, total resistance**

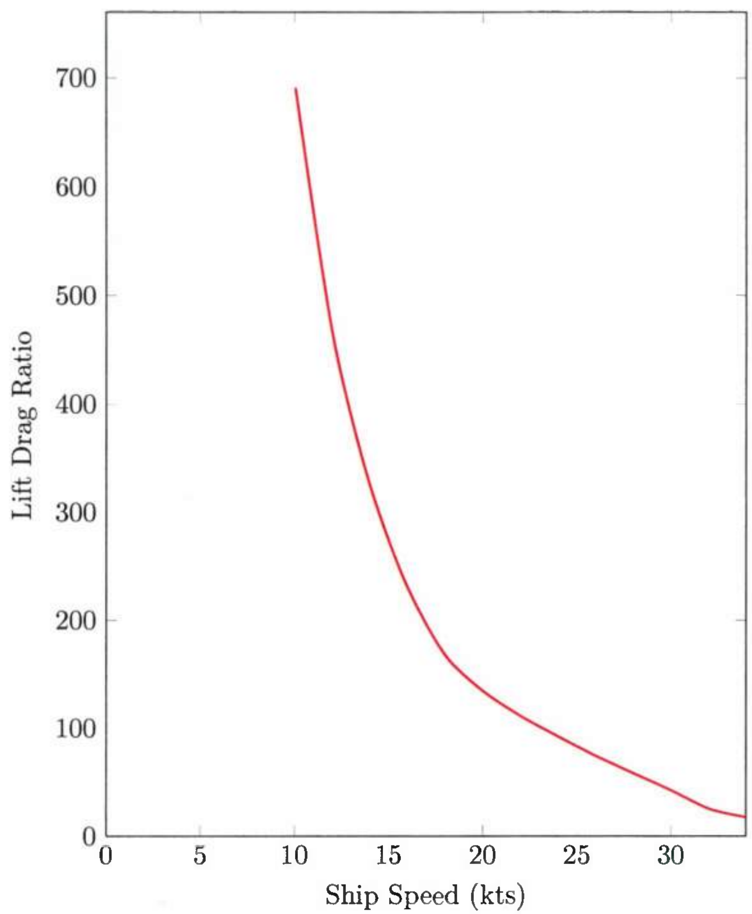



**Figure B-14: Three unit, 0° static trim, test 5, lift drag ratio**

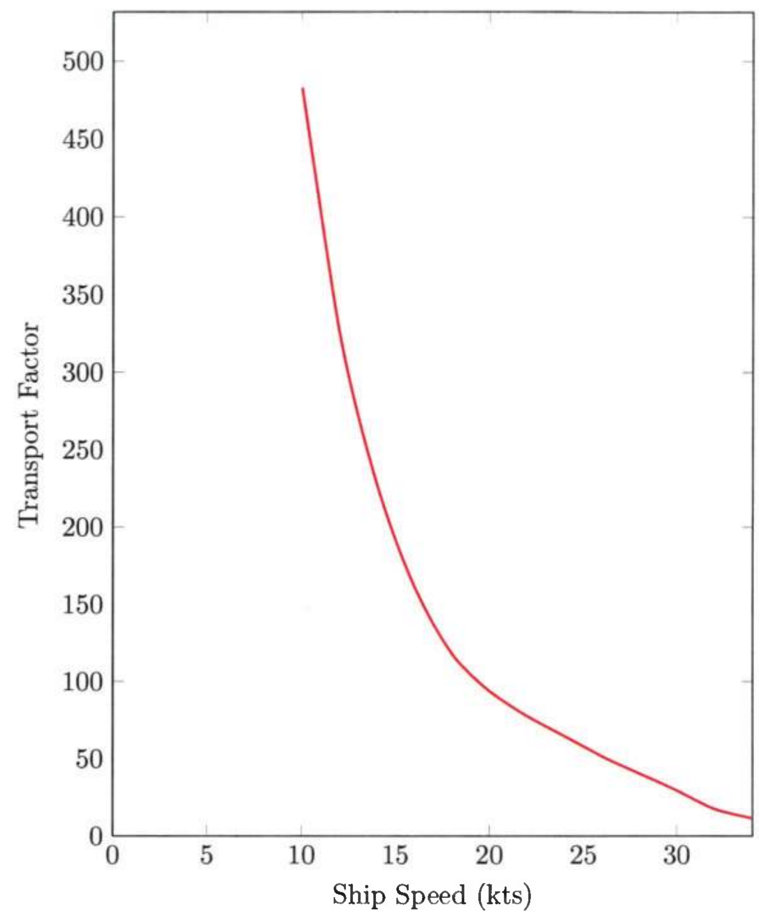



**Figure B-15: Three unit, 0° static trim, test 5, transport factor**

## Four Unit, 0° Static Trim, Test 6

$\lambda = 54.134 \quad T = 19.5$ feet

$\Delta = 42513$ LT $\quad LOA = 2135$ feet

**Table B-6: Four unit, 0° static trim, test 6, resistance data**

| SPEED [kts] | EHP [hp] | $C_R$ $10^3$ | L/D | TF | $C_F$ $10^3$ |
|---|---|---|---|---|---|
| 10 | 3,789 | 0.58 | 771 | 540 | 1.36 |
| 12 | 6,749 | 0.67 | 520 | 364 | 1.32 |
| 14 | 10,790 | 0.72 | 379 | 265 | 1.29 |
| 16 | 16,515 | 0.79 | 283 | 198 | 1.27 |
| 18 | 26,450 | 1.07 | 199 | 139 | 1.25 |
| 20 | 37,546 | 1.17 | 156 | 109 | 1.23 |
| 22 | 49,766 | 1.17 | 129 | 90 | 1.21 |
| 24 | 66,941 | 1.27 | 105 | 73 | 1.2 |
| 26 | 91,736 | 1.48 | 83 | 58 | 1.19 |
| 28 | 125,139 | 1.74 | 65 | 46 | 1.18 |
| 30 | 176,015 | 2.17 | 50 | 35 | 1.16 |
| 32 | 353,682 | 4.36 | 26 | 19 | 1.15 |
| 34 | 550,780 | 6.01 | 18 | 13 | 1.15 |

*TF is transport factor assuming a 0.7 propulsive efficiency

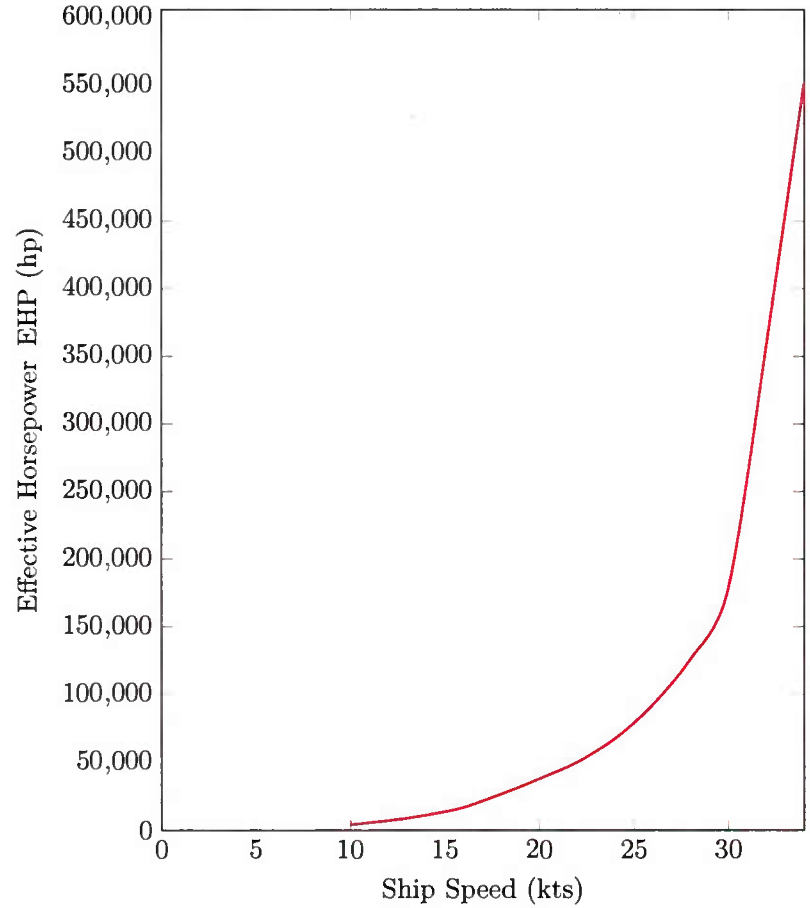



**Figure B-16: Four unit, 0° static trim, test 6, total resistance**

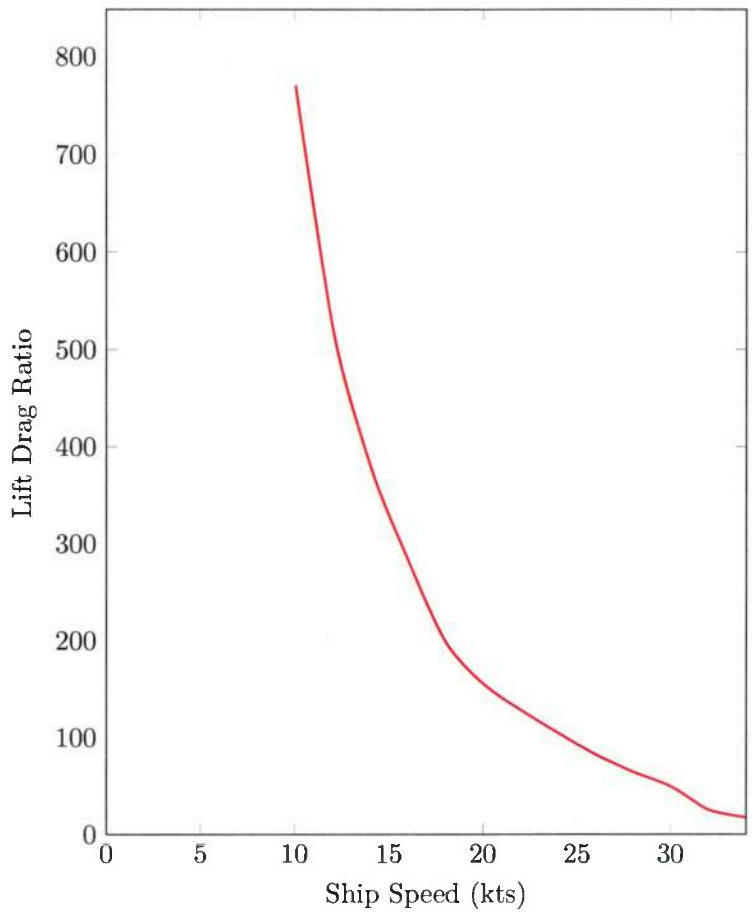



**Figure B-17: Four unit, 0° static trim, test 6, lift drag ratio**

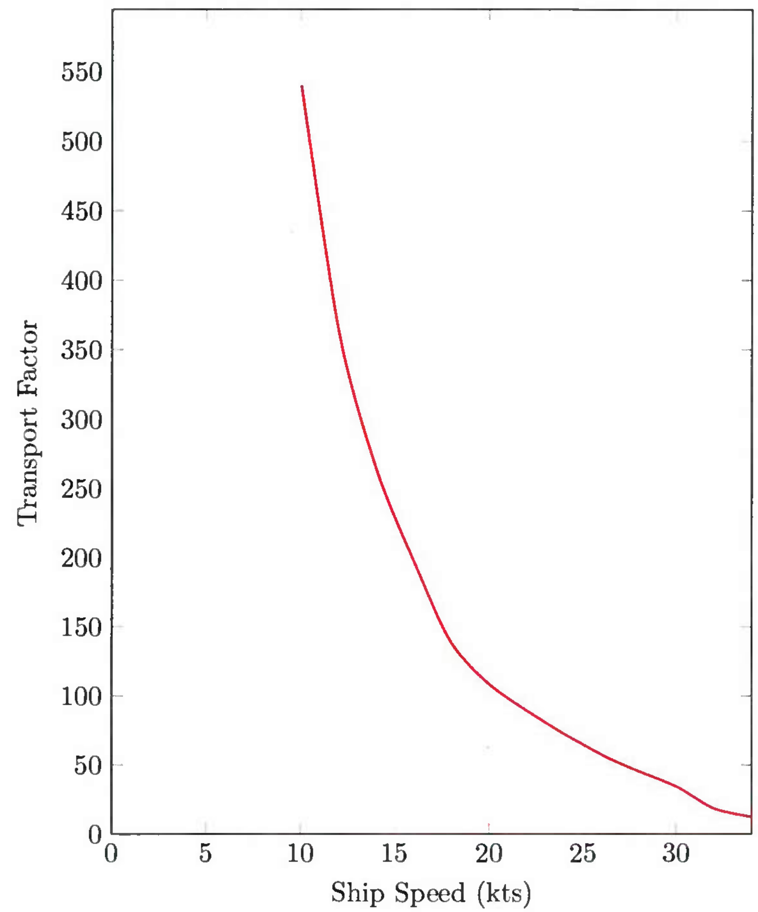



**Figure B-18: Four unit, 0° static trim, test 6, transport factor**

This page intentionally left blank.

# APPENDIX C: INDIVIDUAL RESISTANCE DATA

## Independent Unit, 0° Static Trim, Side Hulls Middle, Test 1

$\lambda$ = 54.134 $T$ = 19.5 feet

$\Delta$ = 10628 LT $LOA$ = 541.3 feet

**Table C-1: Independent Unit, 0° static trim, side hulls middle, test 1, resistance data**

| SPEED [kts] | EHP [hp] | PITCH [deg] | HEAVE [in] | $C_R$ $10^3$ | $C_F$ $10^3$ |
|---|---|---|---|---|---|
| 10 | 1,244 | 0.01 | −0.16 | 0.87 | 1.67 |
| 12 | 2,373 | 0.03 | −0.19 | 1.18 | 1.63 |
| 14 | 3,722 | 0.03 | −0.34 | 1.17 | 1.6 |
| 16 | 5,739 | 0.03 | −0.37 | 1.29 | 1.57 |
| 18 | 9,374 | 0.04 | −0.36 | 1.74 | 1.55 |
| 20 | 12,045 | 0.05 | −0.49 | 1.55 | 1.53 |
| 22 | 16,601 | 0.09 | −0.86 | 1.68 | 1.51 |
| 24 | 22,956 | 0.18 | −1.58 | 1.9 | 1.49 |
| 26 | 31,178 | 0.34 | −2.79 | 2.14 | 1.48 |
| 28 | 42,758 | 0.6 | −4.76 | 2.51 | 1.47 |
| 30 | 58,537 | 0.94 | −7.51 | 2.97 | 1.45 |
| 32 | 84,158 | 1.27 | −10.38 | 3.8 | 1.44 |
| 34 | 113,137 | 1.55 | −12.89 | 4.45 | 1.43 |
| 36 | 139,032 | 1.79 | −15.06 | 4.66 | 1.42 |
| 38 | 163,105 | 2.02 | −16.94 | 4.66 | 1.41 |
| 40 | 187,927 | 2.22 | −18.56 | 4.59 | 1.4 |

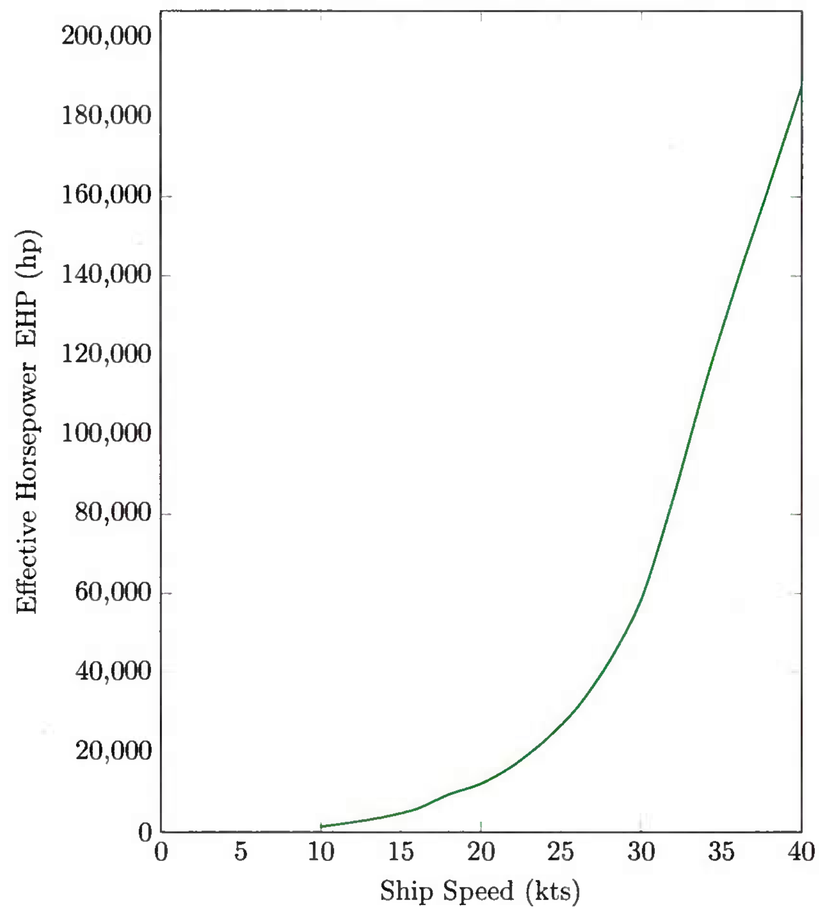



**Figure C-1: Independent Unit, 0° static trim, side hulls middle, test 1, effective power**

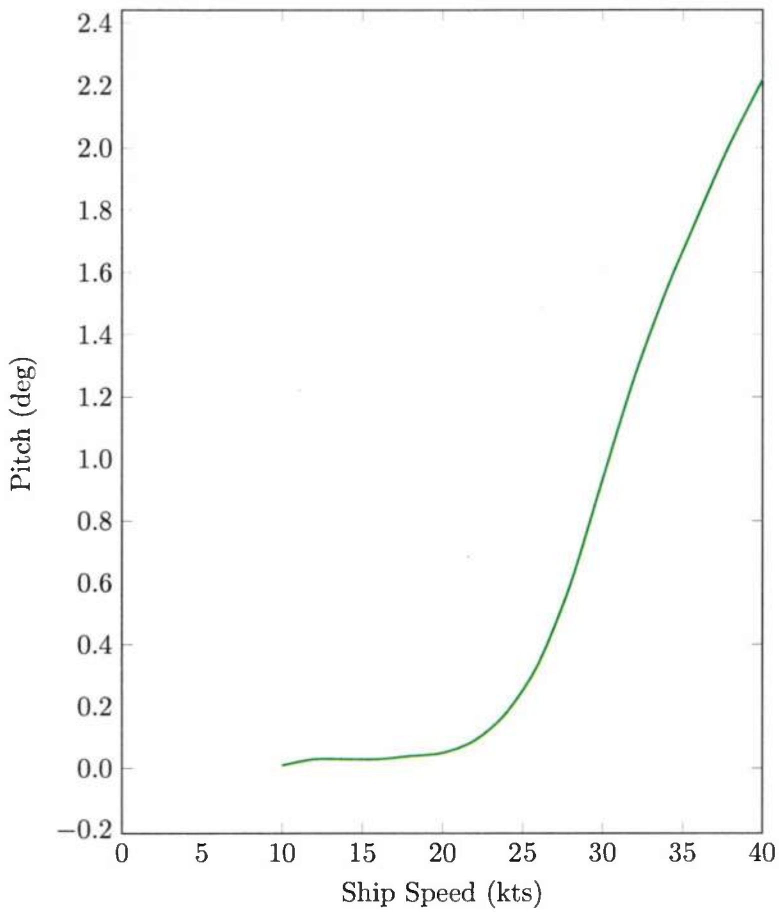



**Figure C-2: Independent Unit, 0° static trim, side hulls middle, test 1, pitch**

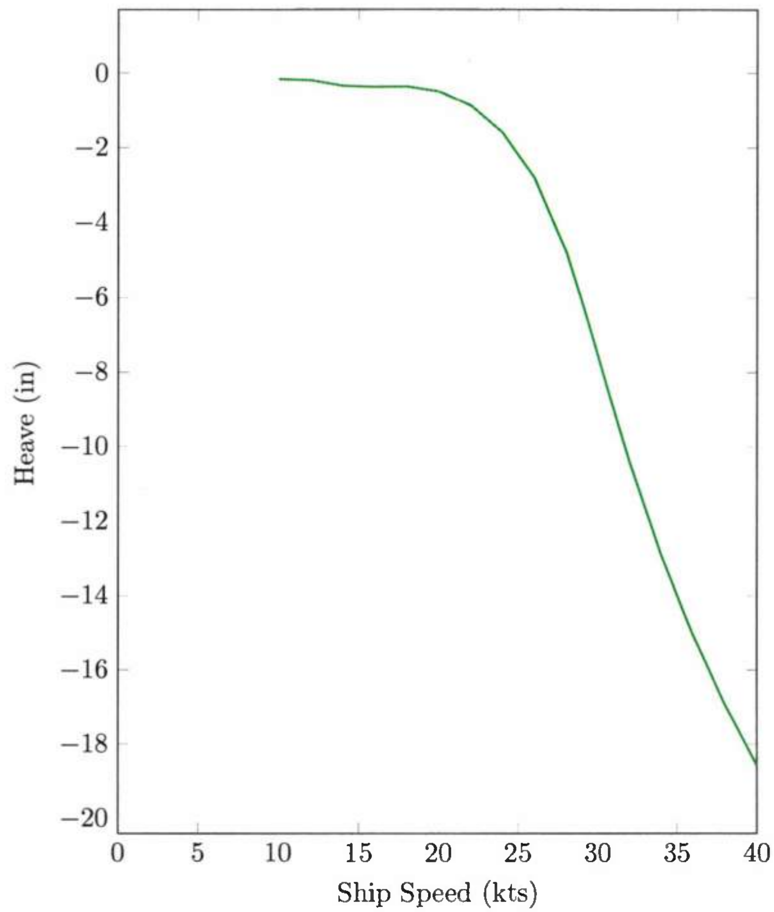



**Figure C-3: Independent Unit, 0° static trim, side hulls middle, test 1, heave**

## Independent Unit, $-1°$ Static Trim, Side Hulls Middle, test 2

$\lambda$ = 54.134 $T$ = 19.5 feet

$\Delta$ = 10628 LT $LOA$ = 541.13 feet

**Table C-2: Independent Unit, $-1°$ static trim, side hulls middle, Test 2, resistance data**

| SPEED [kts] | EHP [hp] | PITCH [deg] | HEAVE [in] | $C_R$ $10^3$ | $C_F$ $10^3$ |
|---|---|---|---|---|---|
| 10 | 1,330 | 0.46 | −0.12 | 1.05 | 1.67 |
| 12 | 3,949 | 0.65 | −0.46 | 1.05 | 3.62 |
| 14 | 6,329 | 0.67 | −0.63 | 1.16 | 3.55 |
| 16 | 10,265 | 0.1 | −0.89 | 1.63 | 3.49 |
| 18 | 15,480 | 0.11 | −1.08 | 1.98 | 3.44 |
| 20 | 20,823 | 0.13 | −1.18 | 1.92 | 3.39 |
| 22 | 27,049 | 0.17 | −1.47 | 1.83 | 3.35 |
| 24 | 35,743 | 0.29 | −2.35 | 1.96 | 3.32 |
| 26 | 48,144 | 0.53 | −4.25 | 2.31 | 3.29 |
| 28 | 66,605 | 0.85 | −7.05 | 2.94 | 3.26 |
| 30 | 90,105 | 1.17 | −10.08 | 3.58 | 3.23 |
| 32 | 123,288 | 1.49 | −12.82 | 4.48 | 3.2 |
| 34 | 161,785 | 1.81 | −15.08 | 5.22 | 3.18 |
| 36 | 193,611 | 2.12 | −17.03 | 5.31 | 3.16 |
| 38 | 226,597 | 2.35 | −18.82 | 5.29 | 3.14 |
| 40 | 263,134 | 2.44 | −20.43 | 5.27 | 3.12 |

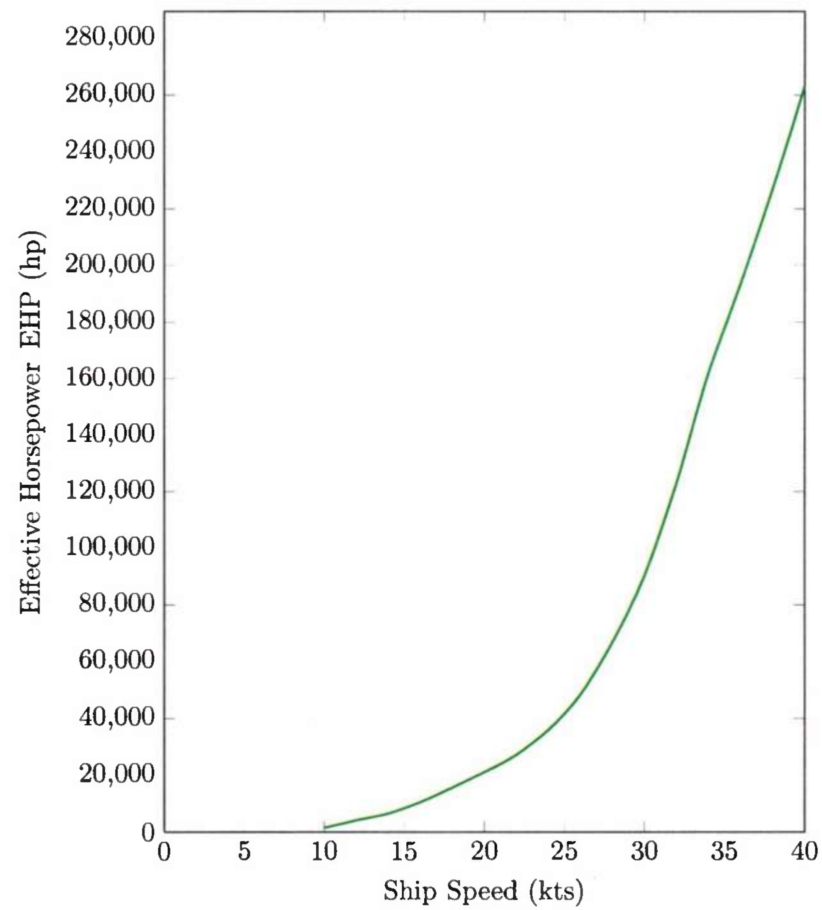



**Figure C-4: Independent Unit, $-1°$ static trim, side hulls middle, Test 2, effective power**

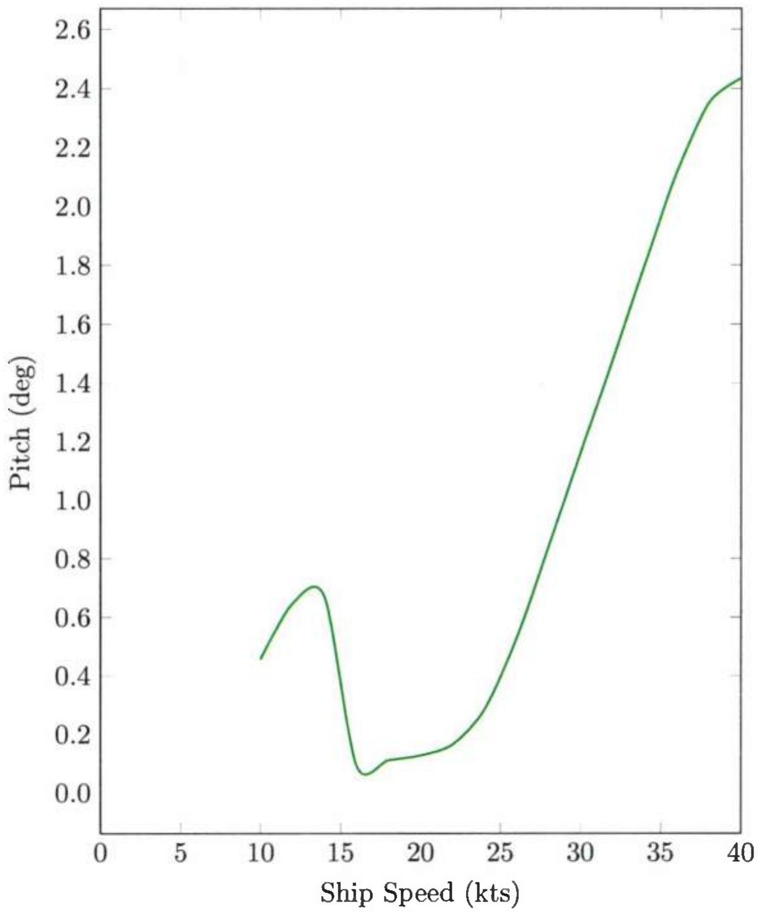



**Figure C-5: Independent Unit, $-1°$ static trim, side hulls middle, Test 2, pitch**

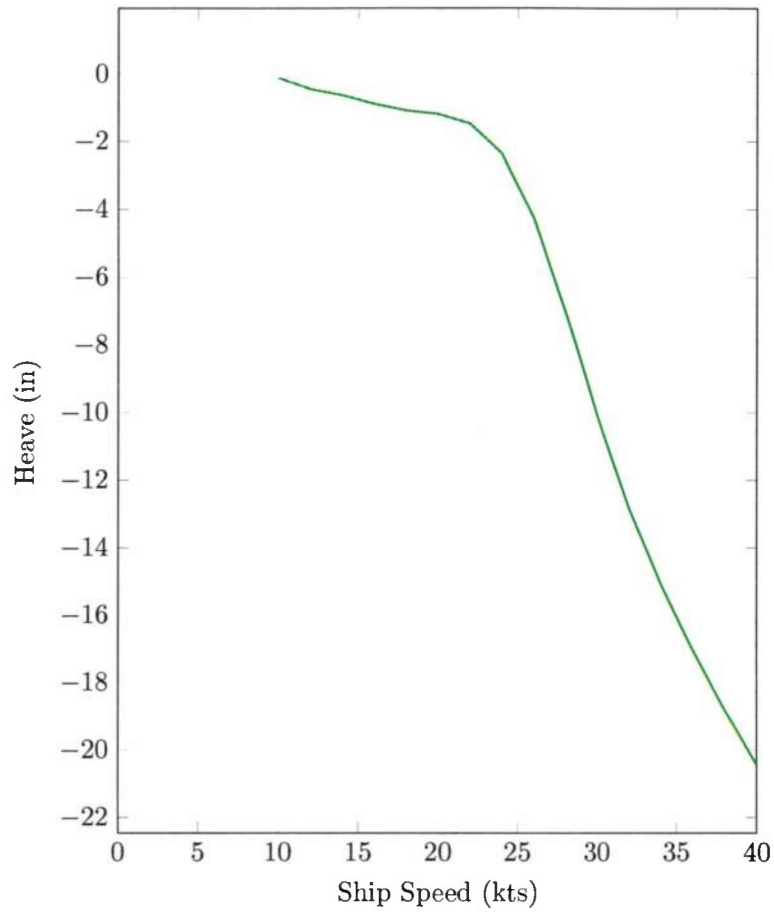



**Figure C-6: Independent Unit, $-1°$ static trim, side hulls middle, Test 2, heave**

## Independent Unit, 0° Static Trim, Side Hulls Aft, Test 3

$\lambda = 54.134 \qquad T = 19.5$ feet

$\Delta = 10628$ LT $\qquad LOA = 541.3$ feet

**Table C-3: Independent Unit, 0° static trim, side hulls aft, test 3, resistance data**

| SPEED [kts] | EHP [hp] | PITCH [deg] | HEAVE [in] | $C_R$ $10^3$ | $C_F$ $10^3$ |
|---|---|---|---|---|---|
| 10 | 1,303 | −0.02 | 0.19 | 0.99 | 1.67 |
| 12 | 3,987 | −0.08 | 0.6 | 1.09 | 3.62 |
| 14 | 6,197 | −0.13 | 0.92 | 1.06 | 3.55 |
| 16 | 10,088 | −0.19 | 1.49 | 1.54 | 3.49 |
| 18 | 13,389 | −0.26 | 2.19 | 1.25 | 3.44 |
| 20 | 17,943 | −0.32 | 2.75 | 1.19 | 3.39 |
| 22 | 25,593 | −0.37 | 3.22 | 1.55 | 3.35 |
| 24 | 39,176 | −0.42 | 3.7 | 2.47 | 3.32 |
| 26 | 55,671 | −0.48 | 4.22 | 3.18 | 3.29 |
| 28 | 73,667 | −0.54 | 4.73 | 3.6 | 3.26 |
| 30 | 97,062 | −0.6 | 5.17 | 4.11 | 3.23 |
| 32 | 121,686 | −0.63 | 5.42 | 4.38 | 3.2 |
| 34 | 144,904 | −0.65 | 5.47 | 4.35 | 3.18 |
| 36 | 168,713 | −0.64 | 5.36 | 4.22 | 3.16 |
| 38 | 193,885 | −0.61 | 5.13 | 4.08 | 3.14 |
| 40 | 218,867 | −0.56 | 4.72 | 3.86 | 3.12 |

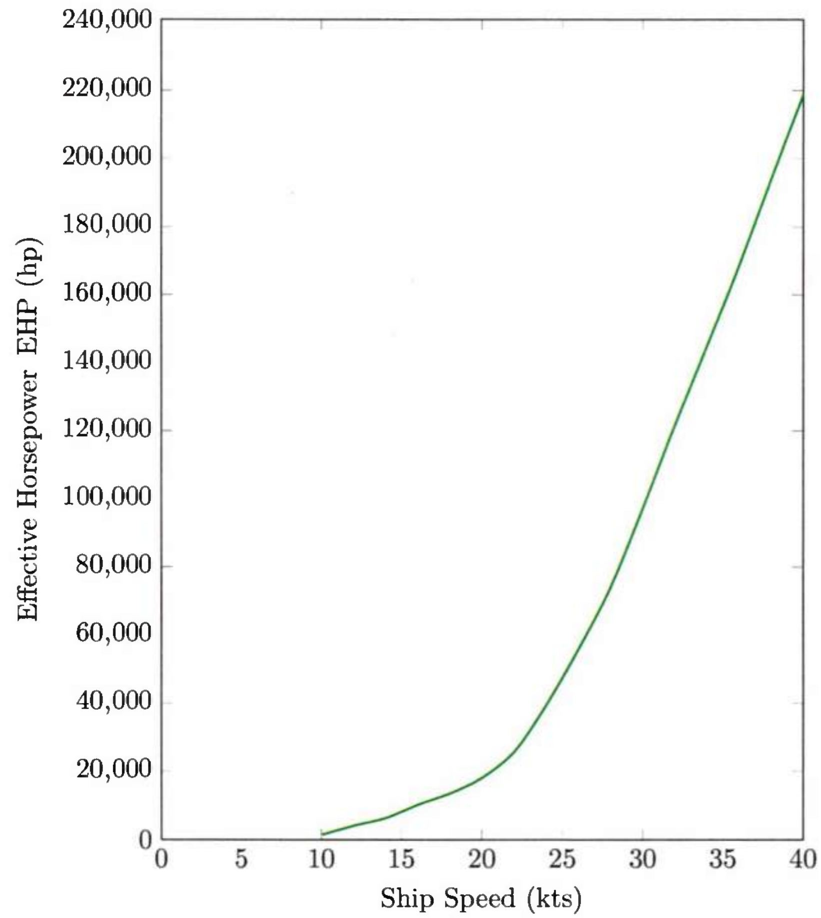



**Figure C-7: Independent Unit, 0° static trim, side hulls aft, test 3, effective power**

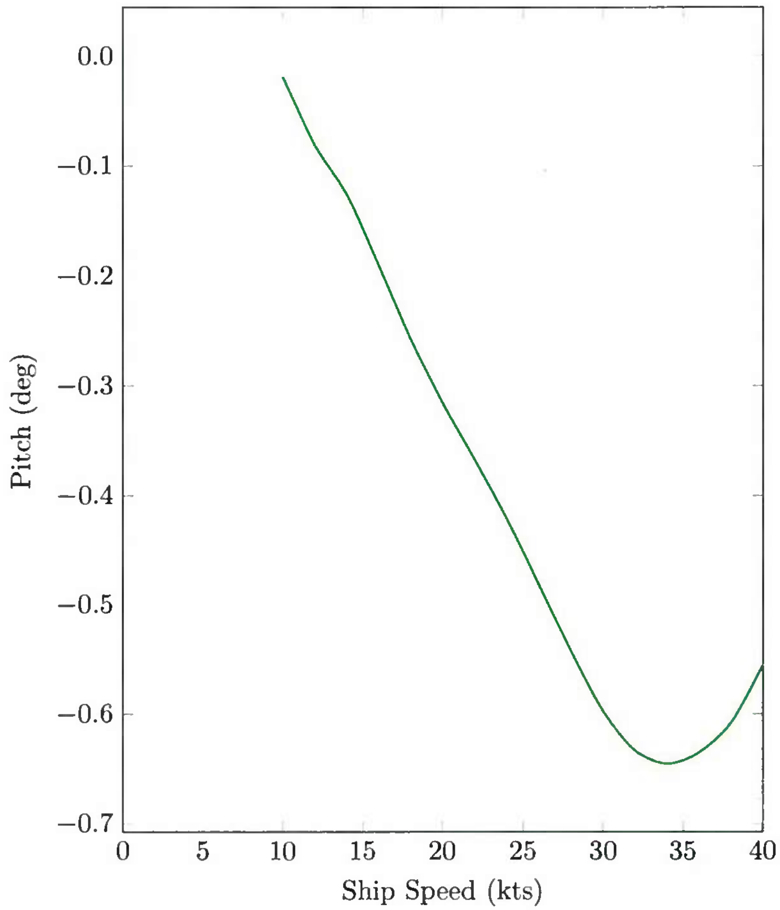



**Figure C-8: Independent Unit, 0° static trim, side hulls aft, test 3, pitch**

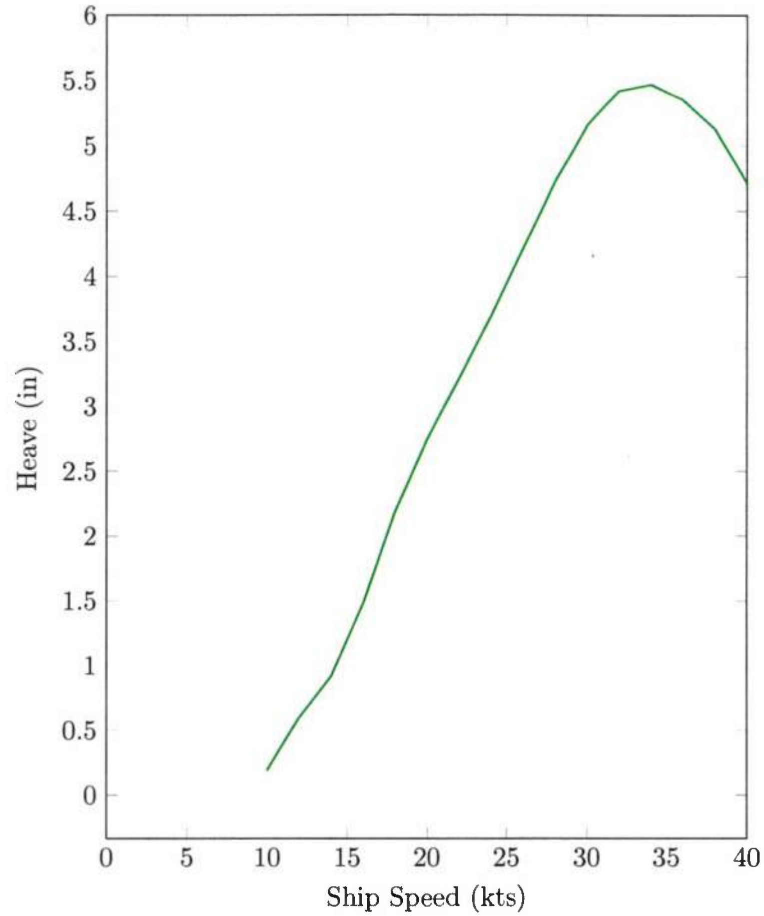



**Figure C-9: Independent Unit, 0° static trim, side hulls aft, test 3, heave**

## Two Unit Seatrain, 0° Static Trim, Test 4

$\lambda = 54.134$ $\quad T = 19.5$ feet

$\Delta = 10628$ LT $\quad LOA = 541.3$ feet

**Table C-4: Unit 1 of two unit seatrain, 0° static trim, test 4, resistance data**

| SPEED [kts] | EHP [hp] | PITCH [deg] | HEAVE [in] | $C_R$ $10^3$ | $C_F$ $10^3$ |
|---|---|---|---|---|---|
| 10 | 965 | −0.07 | −0.01 | 0.31 | 1.67 |
| 12 | 1,713 | 0.01 | 0.02 | 0.41 | 1.62 |
| 14 | 2,828 | 0.02 | 0.02 | 0.52 | 1.59 |
| 16 | 4,426 | 0.01 | −0.02 | 0.65 | 1.57 |
| 18 | 6,611 | 0 | 0.02 | 0.78 | 1.54 |
| 20 | 9,422 | 0 | 0.07 | 0.89 | 1.52 |
| 22 | 12,982 | 0.04 | −0.12 | 1 | 1.5 |
| 24 | 17,503 | 0.13 | −0.74 | 1.11 | 1.49 |
| 26 | 23,359 | 0.25 | −1.84 | 1.25 | 1.47 |
| 28 | 31,462 | 0.46 | −3.7 | 1.48 | 1.46 |
| 30 | 44,990 | 0.82 | −6.57 | 1.97 | 1.45 |
| 32 | 69,139 | 1.19 | −9.48 | 2.89 | 1.44 |
| 34 | 97,034 | 1.43 | −11.81 | 3.64 | 1.43 |
| 36 | 126,457 | 1.67 | −13.95 | 4.14 | 1.42 |
| 38 | 158,604 | 1.9 | −16.07 | 4.52 | 1.41 |

**Table C-5: Unit 2 of two unit seatrain, 0° static trim, test 4, resistance data**

| SPEED [kts] | EHP [hp] | PITCH [deg] | HEAVE [in] | $C_R$ $10^3$ | $C_F$ $10^3$ |
|---|---|---|---|---|---|
| 10 | 1,318 | 0.31 | −0.31 | 1.16 | 1.53 |
| 12 | 2,423 | 0.49 | −0.39 | 1.37 | 1.5 |
| 14 | 3,927 | 0.71 | −0.57 | 1.46 | 1.47 |
| 16 | 5,957 | 0.11 | −0.84 | 1.53 | 1.45 |
| 18 | 8,696 | 0.12 | −1.03 | 1.62 | 1.43 |
| 20 | 12,360 | 0.14 | −1.15 | 1.75 | 1.41 |
| 22 | 17,182 | 0.18 | −1.57 | 1.91 | 1.39 |
| 24 | 23,424 | 0.32 | −2.56 | 2.09 | 1.38 |
| 26 | 31,406 | 0.53 | −3.73 | 2.29 | 1.37 |
| 28 | 42,176 | 0.76 | −5.78 | 2.57 | 1.35 |
| 30 | 63,097 | 1.5 | −12.04 | 3.43 | 1.34 |
| 32 | 107,976 | 2.47 | −20.47 | 5.4 | 1.33 |
| 34 | 163,614 | 3.01 | −24.78 | 7.19 | 1.32 |
| 36 | 210,788 | 3.46 | −27.13 | 7.92 | 1.31 |
| 38 | 227,242 | 3.42 | −28.82 | 7.16 | 1.31 |

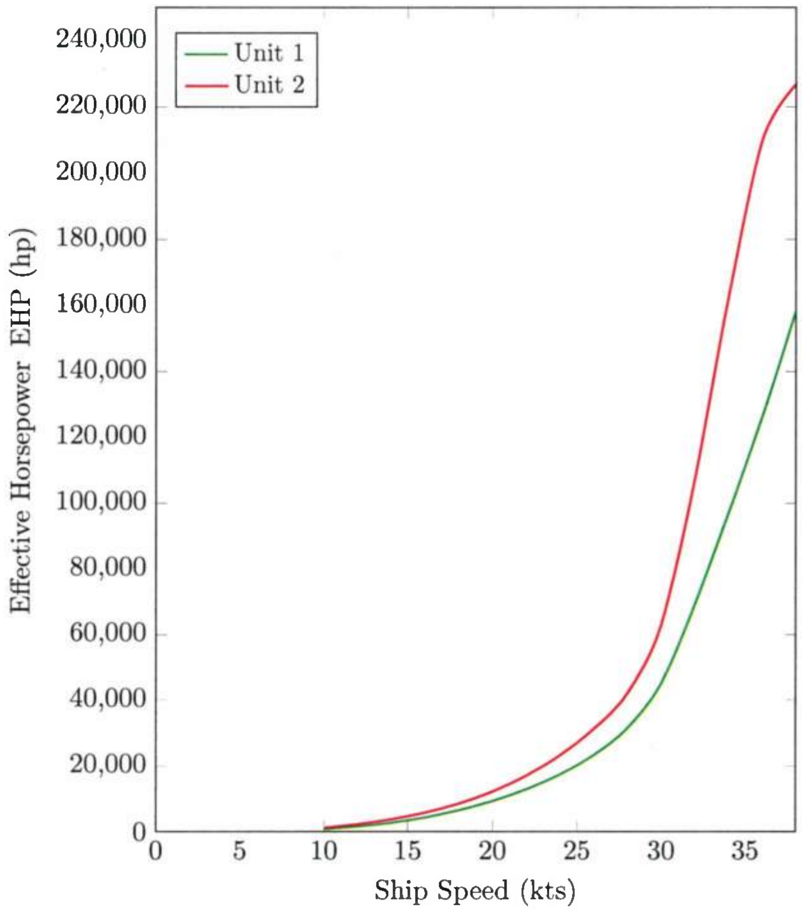



**Figure C-10: Units of two unit seatrain, 0° static trim, test 4, effective power**

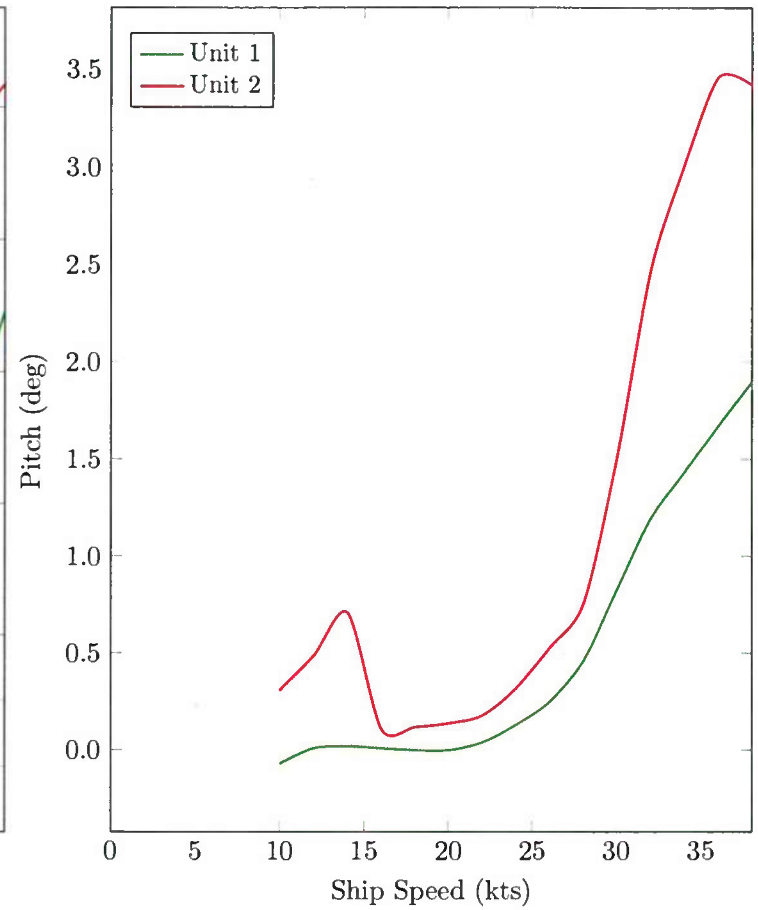



**Figure C-11: Units of two unit seatrain, 0° static trim, test 4, pitch**

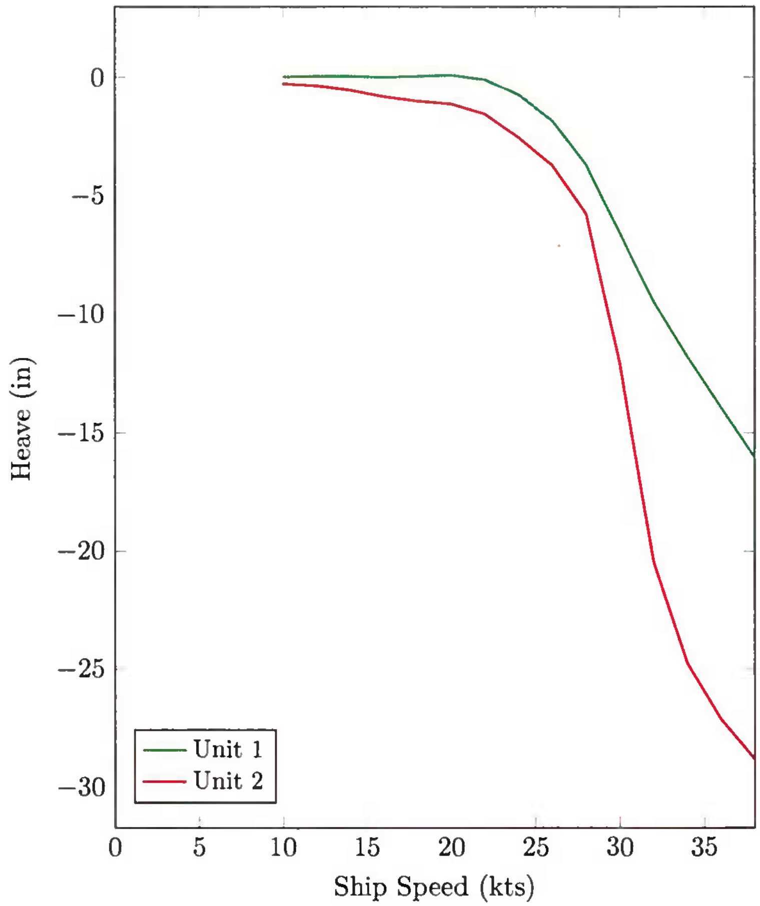



**Figure C-12: Units of two unit seatrain, 0° static trim, test 4, heave**

## Three Unit Seatrain, 0° Static Trim, Test 5

$\lambda = 54.134 \qquad T = 19.5$ feet

$\Delta = 10628$ LT $\quad LOA = 541.3$ feet

**Table C-6: Unit 1 of three unit seatrain, 0° static trim, test 5, resistance data**

| SPEED [kts] | EHP [hp] | PITCH [deg] | HEAVE [in] | $C_R$ $10^3$ | $C_F$ $10^3$ |
|---|---|---|---|---|---|
| 10 | 971 | 0 | 0.03 | 0.32 | 1.67 |
| 12 | 1,744 | 0 | 0.06 | 0.44 | 1.62 |
| 14 | 2,926 | 0 | 0 | 0.59 | 1.59 |
| 16 | 4,807 | 0 | −0.01 | 0.83 | 1.57 |
| 18 | 7,713 | 0 | 0.04 | 1.16 | 1.54 |
| 20 | 9,951 | 0 | 0.03 | 1.02 | 1.52 |
| 22 | 12,866 | 0.02 | −0.16 | 0.97 | 1.5 |
| 24 | 17,342 | 0.08 | −0.71 | 1.08 | 1.49 |
| 26 | 23,624 | 0.2 | −1.81 | 1.27 | 1.47 |
| 28 | 32,554 | 0.43 | −3.48 | 1.57 | 1.46 |
| 30 | 46,692 | 0.78 | −6.1 | 2.09 | 1.45 |
| 32 | 70,165 | 1.09 | −9.08 | 2.94 | 1.44 |
| 34 | 100,615 | 1.4 | −11.69 | 3.81 | 1.43 |

**Table C-7: Unit 2 of three unit seatrain, 0° static trim, test 5, resistance data**

| SPEED [kts] | EHP [hp] | PITCH [deg] | HEAVE [in] | $C_R$ $10^3$ | $C_F$ $10^3$ |
|---|---|---|---|---|---|
| 10 | 973 | 0.02 | −0.21 | 0.47 | 1.52 |
| 12 | 1,731 | 0.03 | −0.12 | 0.57 | 1.48 |
| 14 | 2,942 | 0.05 | −0.2 | 0.74 | 1.46 |
| 16 | 4,771 | 0.05 | −0.34 | 0.95 | 1.43 |
| 18 | 7,215 | 0.08 | −0.47 | 1.12 | 1.41 |
| 20 | 10,203 | 0.12 | −0.71 | 1.21 | 1.39 |
| 22 | 13,672 | 0.18 | −1.11 | 1.25 | 1.38 |
| 24 | 18,160 | 0.25 | −1.76 | 1.32 | 1.37 |
| 26 | 24,099 | 0.37 | −2.85 | 1.45 | 1.35 |
| 28 | 32,481 | 0.57 | −4.89 | 1.68 | 1.34 |
| 30 | 49,296 | 1.24 | −11.02 | 2.4 | 1.33 |
| 32 | 93,512 | 2.29 | −18.87 | 4.51 | 1.32 |
| 34 | 149,752 | 2.89 | −23.83 | 6.48 | 1.31 |

**Table C-8: Unit 3 of three unit seatrain, 0° static trim, test 5, resistance data**

| SPEED [kts] | EHP [hp] | PITCH [deg] | HEAVE [in] | $C_R$ $10^3$ | $C_F$ $10^3$ |
|---|---|---|---|---|---|
| 10 | 1,230 | 0.03 | −0.31 | 1.03 | 1.48 |
| 12 | 2,191 | 0.05 | −0.43 | 1.14 | 1.45 |
| 14 | 3,603 | 0.07 | −0.56 | 1.26 | 1.42 |
| 16 | 5,639 | 0.1 | −0.71 | 1.41 | 1.4 |
| 18 | 8,530 | 0.13 | −0.92 | 1.61 | 1.38 |
| 20 | 12,430 | 0.15 | −1.18 | 1.81 | 1.36 |
| 22 | 16,574 | 0.17 | −1.5 | 1.83 | 1.35 |
| 24 | 21,261 | 0.22 | −2.08 | 1.81 | 1.34 |
| 26 | 28,610 | 0.34 | −3.01 | 2 | 1.32 |
| 28 | 39,484 | 0.58 | −4.87 | 2.37 | 1.31 |
| 30 | 55,909 | 1.22 | −10.23 | 2.93 | 1.3 |
| 32 | 109,623 | 2.38 | −20.39 | 5.55 | 1.29 |
| 34 | 171,605 | 2.97 | −25.2 | 7.64 | 1.28 |

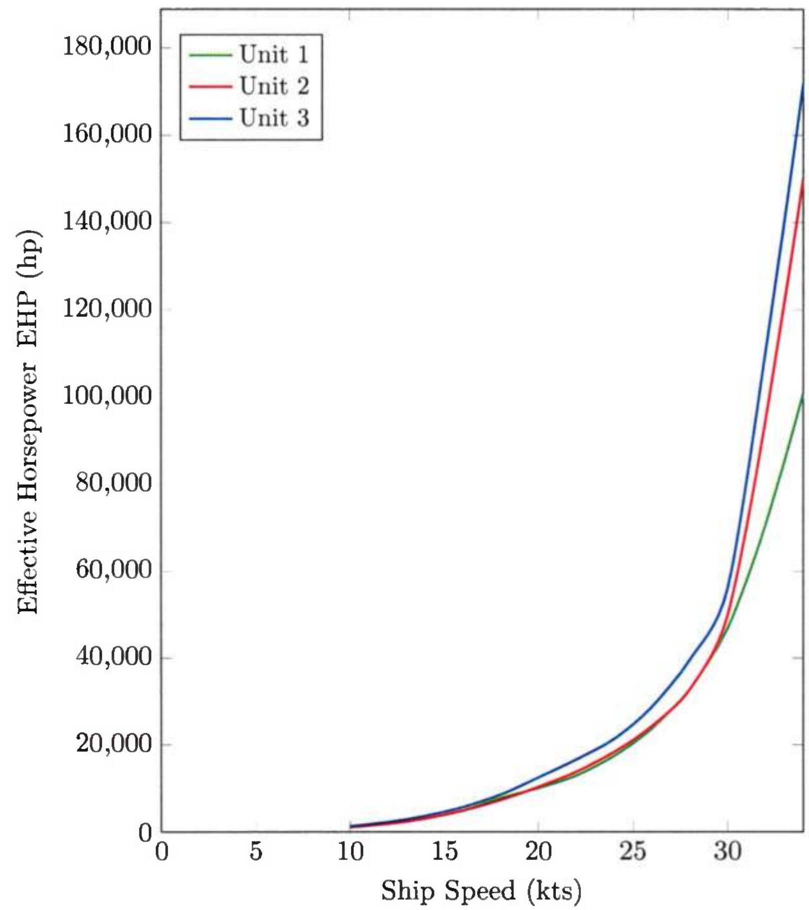



**Figure C-13: Units of three unit seatrain, 0° static trim, test 5, effective power**

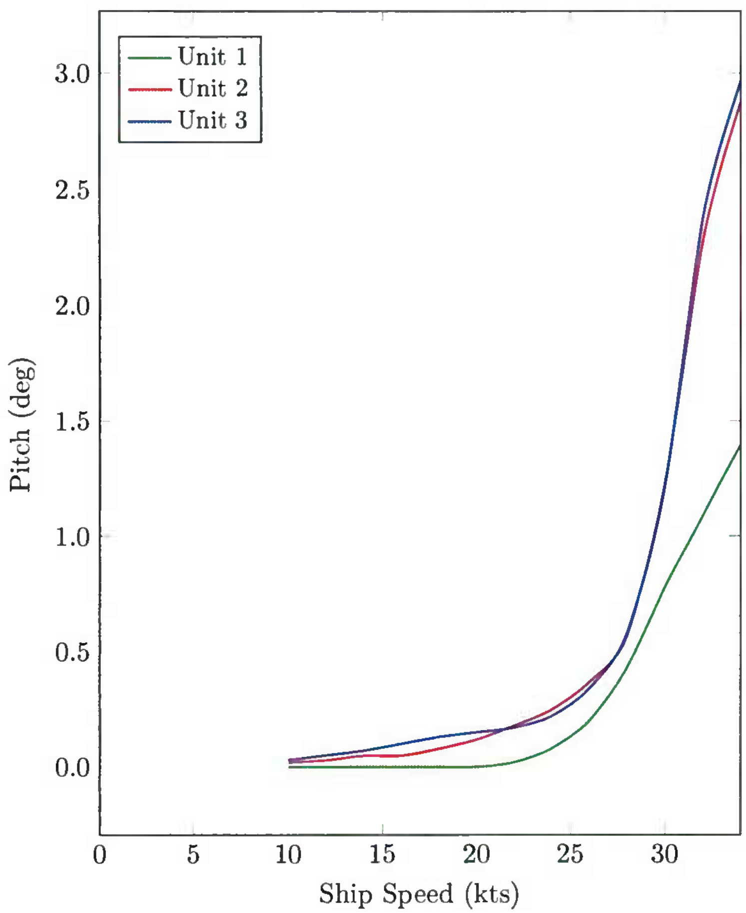



**Figure C-14: Units of three unit seatrain, 0° static trim, test 5, pitch**

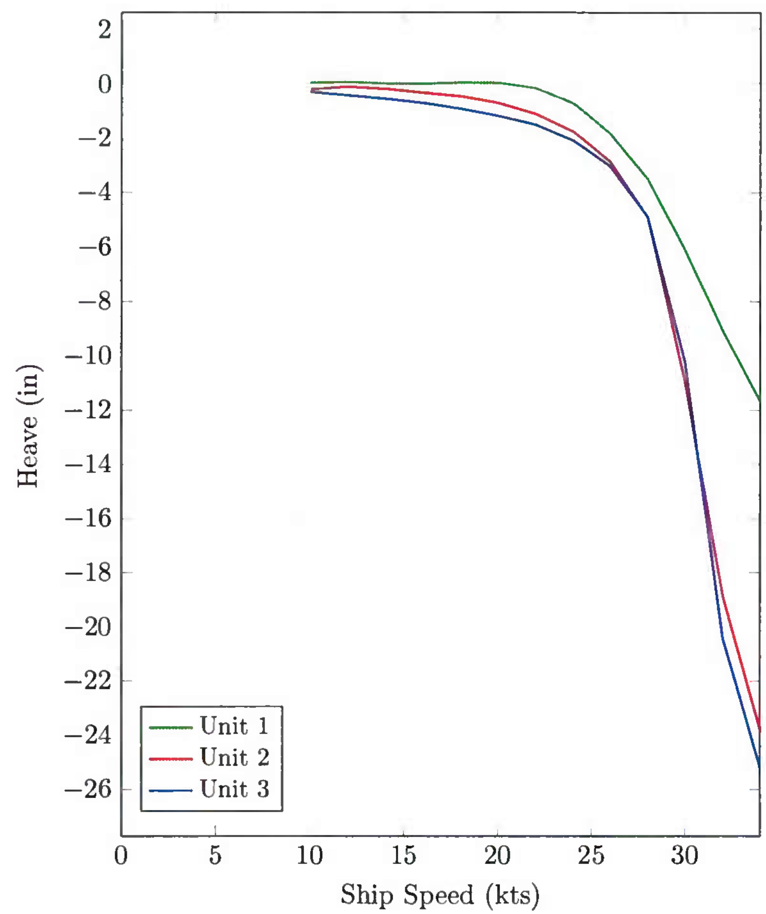



**Figure C-15: Units of three unit seatrain, 0° static trim, test 5, heave**

## Four Unit Seatrain, 0° Static Trim, Test 6

$\lambda = 54.134 \qquad T = 19.5$ feet

$\Delta = 10628$ LT $\quad LOA = 541.3$ feet

**Table C-9: Unit 1 of four unit seatrain, 0° static trim, test 6, resistance data**

| SPEED [kts] | EHP [hp] | PITCH [deg] | HEAVE [in] | $C_R$ $10^3$ | $C_F$ $10^3$ |
|---|---|---|---|---|---|
| 10 | 928 | −0.01 | 0.07 | 0.23 | 1.67 |
| 12 | 1,769 | −0.01 | 0.09 | 0.47 | 1.62 |
| 14 | 2,912 | 0 | 0.02 | 0.58 | 1.59 |
| 16 | 4,505 | 0 | −0.08 | 0.68 | 1.57 |
| 18 | 7,395 | 0 | 0 | 1.05 | 1.54 |
| 20 | 9,618 | −0.01 | 0.02 | 0.94 | 1.52 |
| 22 | 12,474 | 0.01 | −0.14 | 0.89 | 1.5 |
| 24 | 17,554 | 0.09 | −0.73 | 1.11 | 1.49 |
| 26 | 23,648 | 0.23 | −1.79 | 1.28 | 1.47 |
| 28 | 32,165 | 0.42 | −3.72 | 1.53 | 1.46 |
| 30 | 46,534 | 0.77 | −6.45 | 2.07 | 1.45 |
| 32 | 70,112 | 1.11 | −9.19 | 2.94 | 1.44 |
| 34 | 98,745 | 1.38 | −11.59 | 3.71 | 1.43 |

**Table C-10: Unit 2 of four unit seatrain, 0° static trim, test 6, resistance data**

| SPEED [kts] | EHP [hp] | PITCH [deg] | HEAVE [in] | $C_R$ $10^3$ | $C_F$ $10^3$ |
|---|---|---|---|---|---|
| 10 | 1,115 | 0.02 | −0.25 | 0.76 | 1.52 |
| 12 | 1,843 | 0.02 | −0.23 | 0.7 | 1.48 |
| 14 | 2,668 | 0.05 | −0.37 | 0.53 | 1.46 |
| 16 | 4,201 | 0.07 | −0.62 | 0.66 | 1.43 |
| 18 | 7,075 | 0.09 | −0.77 | 1.07 | 1.41 |
| 20 | 9,959 | 0.08 | −0.85 | 1.15 | 1.39 |
| 22 | 13,530 | 0.14 | −1.07 | 1.22 | 1.38 |
| 24 | 18,173 | 0.22 | −1.71 | 1.32 | 1.37 |
| 26 | 23,845 | 0.36 | −3.01 | 1.42 | 1.35 |
| 28 | 31,937 | 0.71 | −6.14 | 1.63 | 1.34 |
| 30 | 48,301 | 1.29 | −11.45 | 2.33 | 1.33 |
| 32 | 88,552 | 2.15 | −17.76 | 4.2 | 1.32 |
| 34 | 152,512 | 3.14 | −24.89 | 6.62 | 1.31 |

Table C-11: **Unit 3 of four unit seatrain, 0° static trim, test 6, resistance data**

| SPEED [kts] | EHP [hp] | PITCH [deg] | HEAVE [in] | $C_R$ $10^3$ | $C_F$ $10^3$ |
|---|---|---|---|---|---|
| 10 | 762 | 0.03 | −0.29 | 0.79 | 0.77 |
| 12 | 1,416 | 0.04 | −0.34 | 0.93 | 0.75 |
| 14 | 2,394 | 0.06 | −0.46 | 1.05 | 0.73 |
| 16 | 3,534 | 0.07 | −0.66 | 1.05 | 0.72 |
| 18 | 5,702 | 0.09 | −0.82 | 1.29 | 0.71 |
| 20 | 8,825 | 0.1 | −0.93 | 1.56 | 0.7 |
| 22 | 11,322 | 0.13 | −1.05 | 1.48 | 0.69 |
| 24 | 14,715 | 0.22 | −1.77 | 1.49 | 0.68 |
| 26 | 21,771 | 0.33 | −2.79 | 1.85 | 0.68 |
| 28 | 31,464 | 0.51 | −4.29 | 2.26 | 0.67 |
| 30 | 40,370 | 1.15 | −9.59 | 2.39 | 0.67 |
| 32 | 96,451 | 2.31 | −18.43 | 5.36 | 0.66 |
| 34 | 142,812 | 2.97 | −24.75 | 6.77 | 0.66 |

Table C-12: **Unit 4 of four unit seatrain, 0° static trim, test 6, resistance data**

| SPEED [kts] | EHP [hp] | PITCH [deg] | HEAVE [in] | $C_R$ $10^3$ | $C_F$ $10^3$ |
|---|---|---|---|---|---|
| 10 | 984 | 0.02 | −0.29 | 0.55 | 1.47 |
| 12 | 1,720 | 0.04 | −0.34 | 0.62 | 1.42 |
| 14 | 2,817 | 0.07 | −0.55 | 0.72 | 1.38 |
| 16 | 4,276 | 0.1 | −0.91 | 0.79 | 1.35 |
| 18 | 6,279 | 0.13 | −1.16 | 0.88 | 1.32 |
| 20 | 9,144 | 0.13 | −1.24 | 1.04 | 1.29 |
| 22 | 12,440 | 0.16 | −1.38 | 1.12 | 1.27 |
| 24 | 16,498 | 0.23 | −2 | 1.19 | 1.25 |
| 26 | 22,471 | 0.36 | −3.12 | 1.38 | 1.23 |
| 28 | 29,572 | 0.58 | −5.04 | 1.54 | 1.22 |
| 30 | 40,810 | 1.07 | −8.74 | 1.89 | 1.2 |
| 32 | 98,567 | 2.43 | −20.62 | 4.96 | 1.19 |
| 34 | 156,711 | 2.82 | −23.57 | 6.97 | 1.18 |

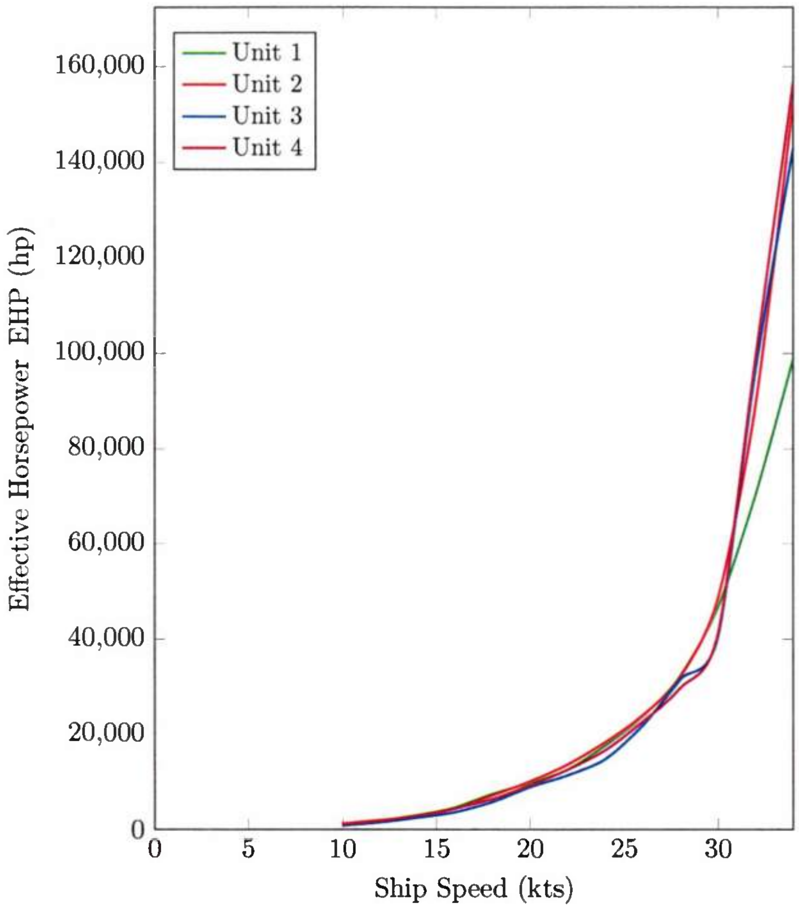



**Figure C-16: Units of four unit seatrain, 0° static trim, test 6, effective power**

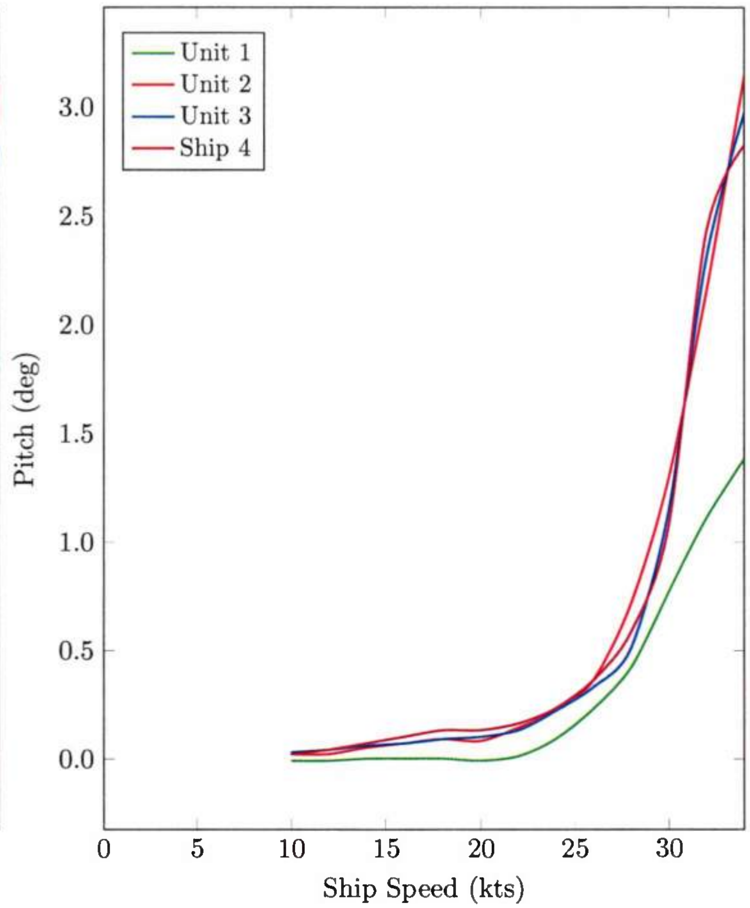



**Figure C-17: Units of four unit seatrain, 0° static trim, test 6, pitch**

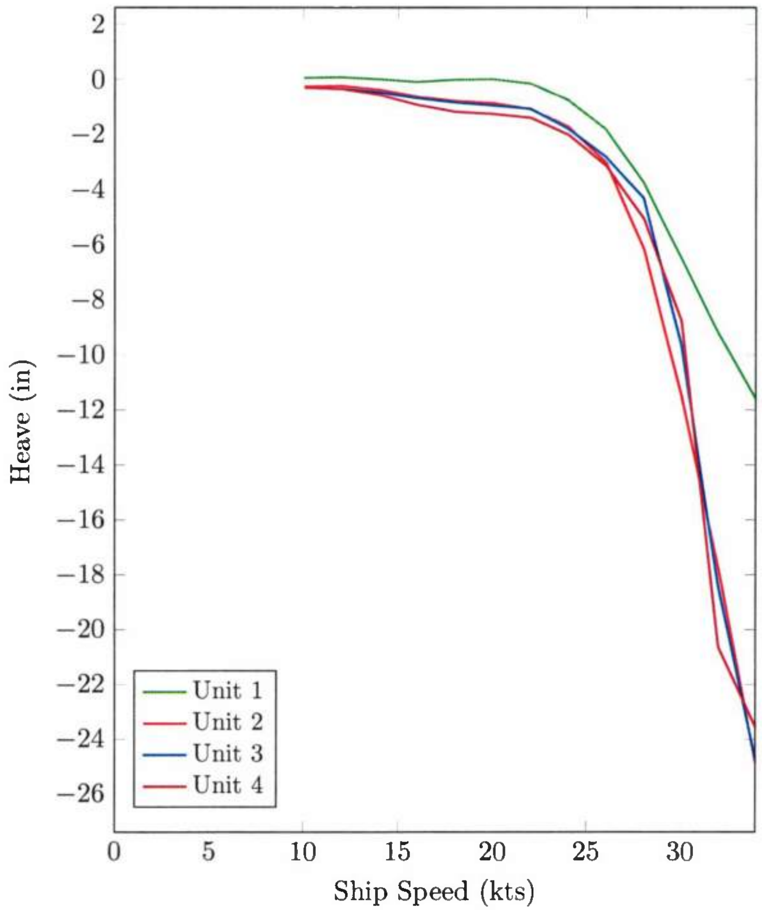



**Figure C-18: Units of four unit seatrain, 0° static trim, test 6, heave**

This page intentionally left blank.

# APPENDIX D: LONGITUDINAL FLOW THROUGH THE PROPELLER PLANE

Table D-1: Free-Wheeling propeller RPM, no powered propeller wash

| $V_{ship}$ [kts] | Indiv Unit [rpm] | Unit 1 of 4 [rpm] | Unit 2 of 4 [rpm] | Unit 3 of 4 [rpm] | Unit 4 of 4 [rpm] |
|---|---|---|---|---|---|
| 10 | 235.91 | 254.68 | 225.35 | 200.61 | 218.34 |
| 12 | 275.53 | 294.30 | 279.11 | 257.16 | 255.26 |
| 14 | 329.39 | 348.15 | 330.17 | 307.89 | 301.27 |
| 16 | 391.68 | 410.44 | 381.04 | 355.97 | 353.52 |
| 18 | 458.10 | 476.86 | 434.13 | 404.68 | 409.70 |
| 20 | 525.70 | 544.47 | 491.53 | 457.05 | 468.31 |
| 22 | 592.74 | 611.51 | 554.87 | 515.59 | 528.80 |
| 24 | 658.50 | 677.27 | 625.13 | 581.98 | 591.85 |
| 26 | 723.16 | 741.93 | 702.44 | 656.79 | 659.56 |
| 28 | 787.61 | 806.38 | 785.94 | 739.17 | 735.65 |
| 30 | 853.34 | 872.11 | 873.60 | 826.52 | 825.70 |
| 32 | 922.23 | 940.99 | 962.00 | 914.24 | 937.33 |
| 34 | 996.42 | 1,015.19 | 1,046.23 | 995.41 | 1,080.45 |

Table D-2: Free-Wheeling propeller RPM as percentage of independent onit, no powered propeller wash

| $V_{ship}$ [kts] | Indiv Unit [%] | Unit 1 of 4 [%] | Unit 2 of 4 [%] | Unit 3 of 4 [%] | Unit 4 of 4 [%] |
|---|---|---|---|---|---|
| 10 | 100.00 | 107.95 | 95.52 | 85.04 | 92.55 |
| 12 | 100.00 | 106.81 | 101.30 | 93.33 | 92.64 |
| 14 | 100.00 | 105.70 | 100.24 | 93.47 | 91.46 |
| 16 | 100.00 | 104.79 | 97.28 | 90.88 | 90.26 |
| 18 | 100.00 | 104.10 | 94.77 | 88.34 | 89.44 |
| 20 | 100.00 | 103.57 | 93.50 | 86.94 | 89.08 |
| 22 | 100.00 | 103.17 | 93.61 | 86.98 | 89.21 |
| 24 | 100.00 | 102.85 | 94.93 | 88.38 | 89.88 |
| 26 | 100.00 | 102.60 | 97.13 | 90.82 | 91.21 |
| 28 | 100.00 | 102.38 | 99.79 | 93.85 | 93.40 |
| 30 | 100.00 | 102.20 | 102.37 | 96.86 | 96.76 |
| 32 | 100.00 | 102.03 | 104.31 | 99.13 | 101.64 |
| 34 | 100.00 | 101.88 | 105.00 | 99.90 | 108.43 |

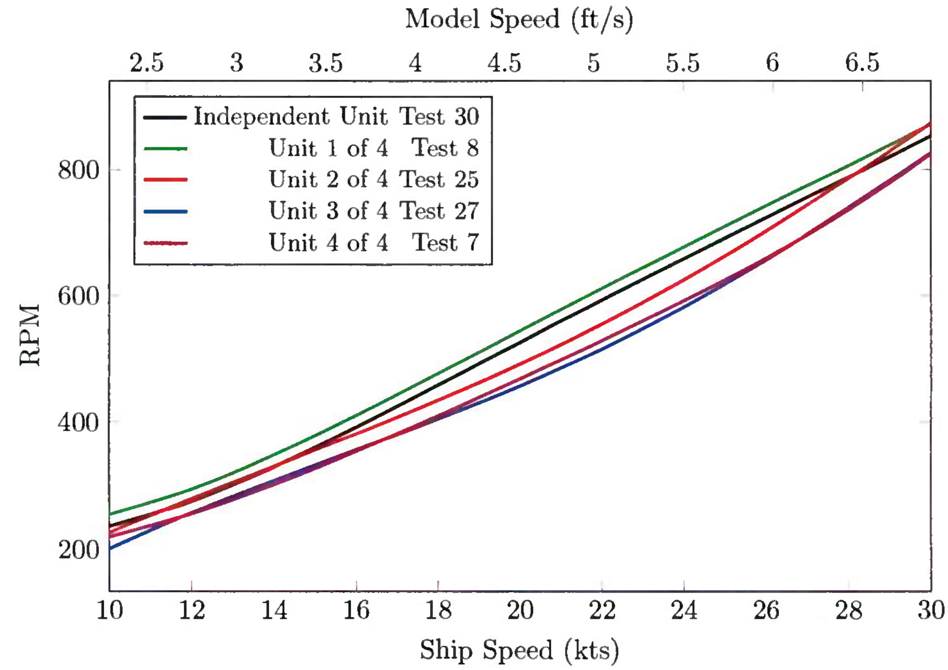



**Figure D-1: Free-wheeling propeller RPM**

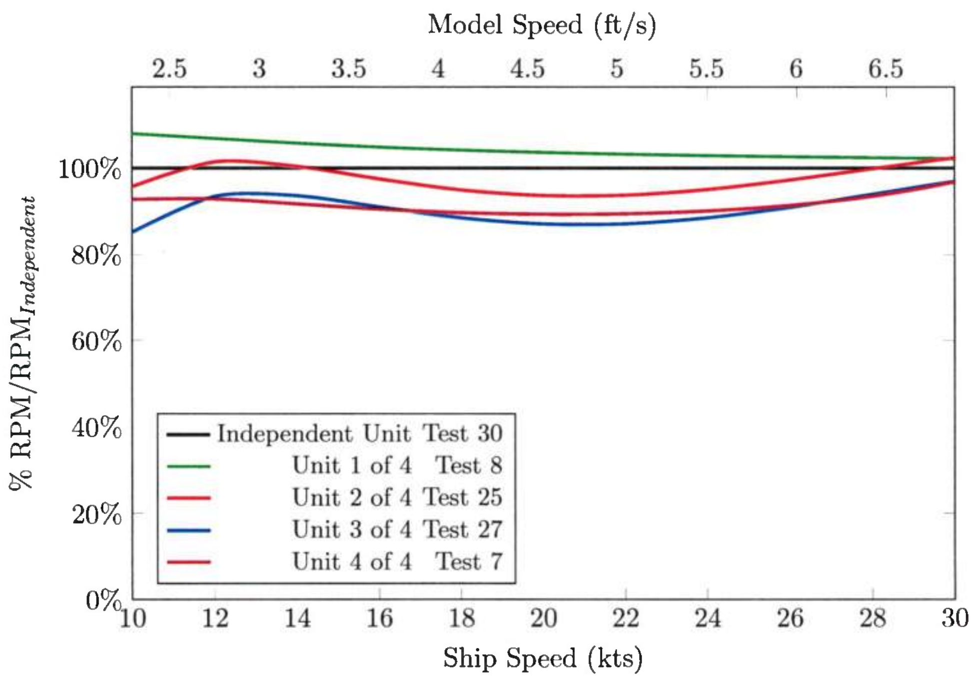



**Figure D-2: Free-wheeling propeller RPM as percentage of independent unit RPM**

Table D-3: Free-Wheeling propeller RPM, powered propeller wash

| $V_{ship}$ [kts] | Indiv Unit [rpm] | Unit 1 of 4 [rpm] | Unit 2 of 4 [rpm] | Unit 3 of 4 [rpm] | Unit 4 of 4 [rpm] |
|---|---|---|---|---|---|
| 10 | 235.91 | | 217.73 | 221.64 | |
| 12 | 275.53 | | 288.66 | 277.91 | |
| 14 | 329.39 | | 346.87 | 334.06 | |
| 16 | 391.68 | | 402.28 | 390.63 | |
| 18 | 458.10 | | 460.77 | 448.96 | |
| 20 | 525.70 | | 525.07 | 510.82 | |
| 22 | 592.74 | | 595.58 | 577.94 | |
| 24 | 658.50 | | 671.33 | 651.68 | |
| 26 | 723.16 | | 750.78 | 732.60 | |
| 28 | 787.61 | | 832.77 | 820.09 | |
| 30 | 853.34 | | 917.35 | 911.94 | |
| 32 | 922.23 | | 1,006.67 | 1,003.96 | |
| 34 | 996.42 | | 1,105.89 | 1,089.58 | |

Table D-4: Free-Wheeling propeller RPM as percentage of independent unit, powered propeller wash

| $V_{ship}$ [kts] | Indiv Unit [%] | Unit 1 of 4 [%] | Unit 2 of 4 [%] | Unit 3 of 4 [%] | Unit 4 of 4 [rpm] |
|---|---|---|---|---|---|
| 10 | 100.00 | | 92.29 | 93.95 | |
| 12 | 100.00 | | 104.77 | 100.86 | |
| 14 | 100.00 | | 105.31 | 101.42 | |
| 16 | 100.00 | | 102.71 | 99.73 | |
| 18 | 100.00 | | 100.58 | 98.01 | |
| 20 | 100.00 | | 99.88 | 97.17 | |
| 22 | 100.00 | | 100.48 | 97.50 | |
| 24 | 100.00 | | 101.95 | 98.96 | |
| 26 | 100.00 | | 103.82 | 101.31 | |
| 28 | 100.00 | | 105.73 | 104.12 | |
| 30 | 100.00 | | 107.50 | 106.87 | |
| 32 | 100.00 | | 109.16 | 108.86 | |
| 34 | 100.00 | | 110.99 | 109.35 | |

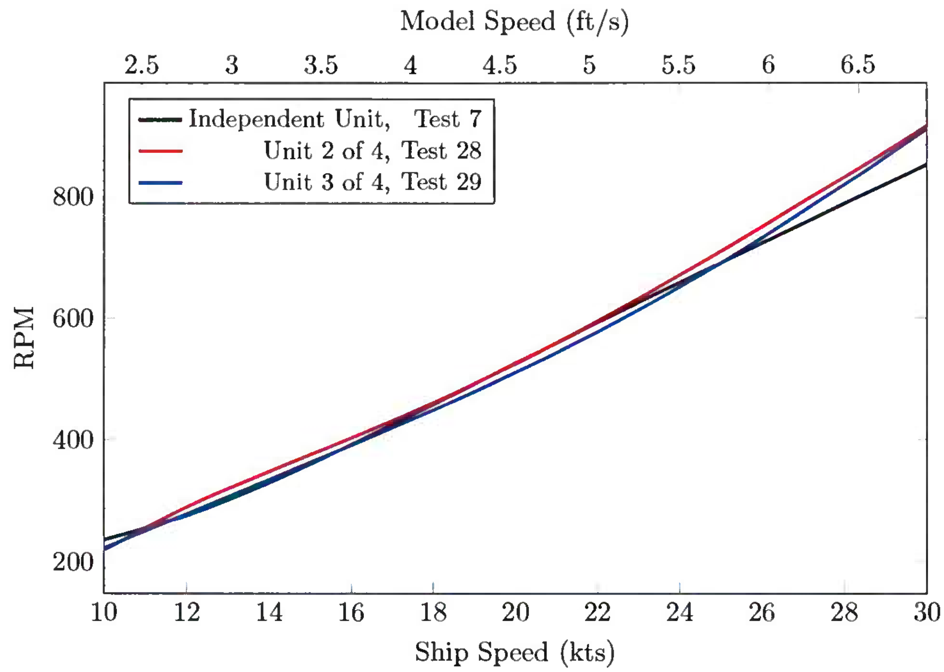



**Figure D-3: Free-wheeling propeller RPM, powered propeller wash**

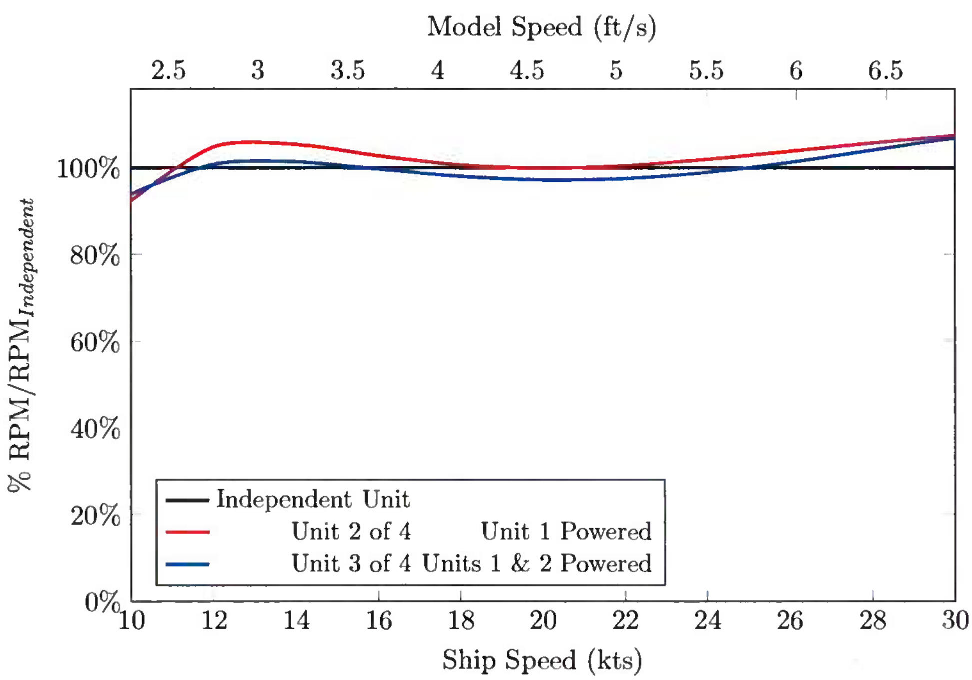



**Figure D-4: Free-wheeling propeller RPM as percentage of independent unit RPM, powered propeller wash**

This page intentionally left blank.

# APPENDIX E: SINGLE UNIT FORCES & MOMENTS

All velocities are given in full-scale. The forces and moments are all given in model scale units.

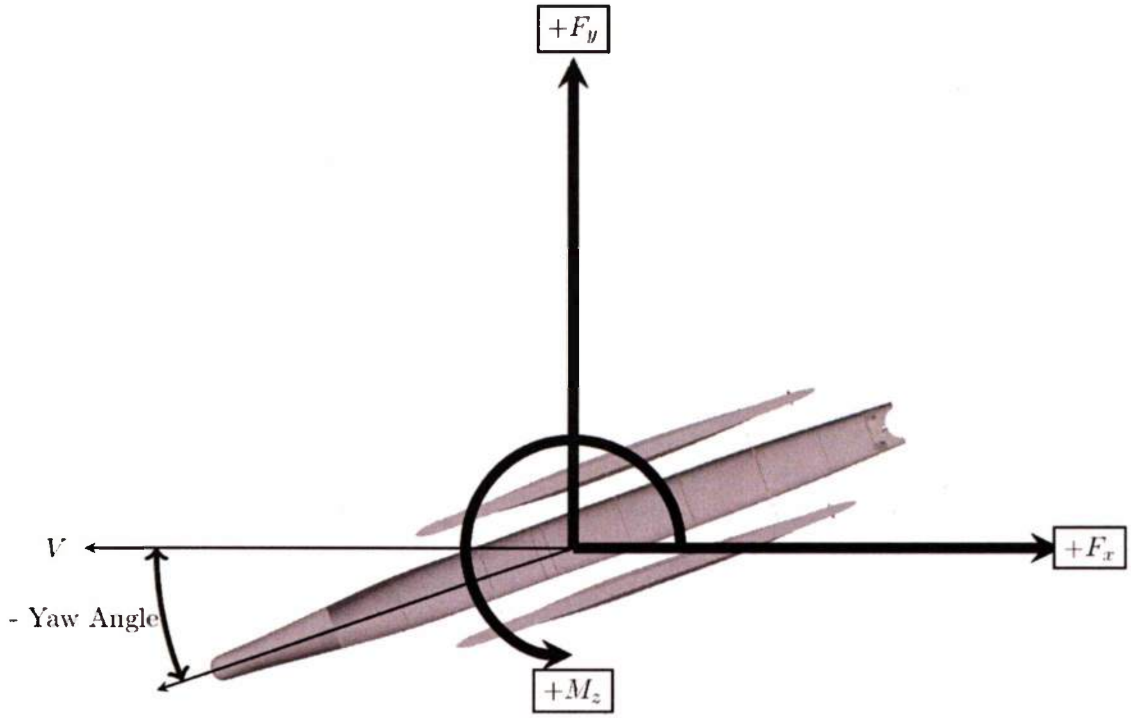



**Figure E-1: Trimaran force moment diagram**

## Single Unit, Free to Heave, Pitch, and Roll Fixed at Various Yaw Angles

**Table E-1:** 0° degree yaw, single unit, free to heave, pitch, & roll

| $V_{model}$ [ft/s] | $F_x$ [lbs] | $F_y$ [lbs] | $F_z$ [lbs] | $M_x$ [in-lbs] | $M_y$ [in-lbs] | $M_z$ [in-lbs] | $V_{ship}$ [kts] |
|---|---|---|---|---|---|---|---|
| 2.29 | 0.93 | 0.60 | −0.01 | −0.21 | −4.86 | −2.95 | 10 |
| 2.52 | 0.99 | 0.58 | 0.01 | −0.18 | −5.17 | −2.59 | 11 |
| 2.75 | 1.07 | 0.54 | 0.02 | −0.15 | −5.49 | −2.24 | 12 |
| 2.98 | 1.15 | 0.50 | 0.04 | −0.12 | −5.83 | −1.94 | 13 |
| 3.21 | 1.23 | 0.46 | 0.06 | −0.09 | −6.21 | −1.73 | 14 |
| 3.44 | 1.33 | 0.42 | 0.09 | −0.06 | −6.64 | −1.64 | 15 |
| 3.67 | 1.44 | 0.38 | 0.11 | −0.03 | −7.13 | −1.70 | 16 |
| 3.9 | 1.56 | 0.35 | 0.14 | 0.00 | −7.69 | −1.95 | 17 |
| 4.13 | 1.70 | 0.32 | 0.17 | 0.02 | −8.32 | −2.42 | 18 |
| 4.36 | 1.86 | 0.30 | 0.19 | 0.03 | −9.05 | −3.14 | 19 |
| 4.59 | 2.04 | 0.30 | 0.23 | 0.04 | −9.89 | −4.16 | 20 |
| 4.82 | 2.25 | 0.30 | 0.26 | 0.04 | −10.84 | −5.50 | 21 |
| 5.05 | 2.47 | 0.33 | 0.29 | 0.02 | −11.91 | −7.20 | 22 |
| 5.28 | 2.73 | 0.37 | 0.33 | 0.00 | −13.13 | −9.28 | 23 |
| 5.51 | 3.01 | 0.44 | 0.36 | −0.04 | −14.49 | −11.80 | 24 |
| 5.74 | 3.32 | 0.52 | 0.40 | −0.09 | −16.01 | −14.78 | 25 |
| 5.96 | 3.67 | 0.64 | 0.44 | −0.16 | −17.71 | −18.25 | 26 |
| 6.19 | 4.05 | 0.78 | 0.48 | −0.24 | −19.58 | −22.25 | 27 |
| 6.42 | 4.47 | 0.95 | 0.52 | −0.35 | −21.66 | −26.81 | 28 |
| 6.65 | 4.93 | 1.15 | 0.56 | −0.47 | −23.94 | −31.97 | 29 |
| 6.88 | 5.43 | 1.39 | 0.60 | −0.62 | −26.43 | −37.76 | 30 |

**Table E-2:** 2.5° degree yaw, single unit, free to heave, pitch, & roll

| $V_{model}$ [ft/s] | $F_x$ [lbs] | $F_y$ [lbs] | $F_z$ [lbs] | $M_x$ [in-lbs] | $M_y$ [in-lbs] | $M_z$ [in-lbs] | $V_{ship}$ [kts] |
|---|---|---|---|---|---|---|---|
| 2.29 | 0.59 | −0.22 | −0.27 | −0.24 | −2.73 | 12.26 | 10 |
| 2.52 | 0.68 | −0.27 | −0.25 | −0.37 | −3.15 | 13.74 | 11 |
| 2.75 | 0.78 | −0.33 | −0.23 | −0.52 | −3.62 | 15.46 | 12 |
| 2.98 | 0.90 | −0.40 | −0.21 | −0.68 | −4.14 | 17.50 | 13 |
| 3.21 | 1.03 | −0.47 | −0.18 | −0.85 | −4.71 | 19.91 | 14 |
| 3.44 | 1.17 | −0.55 | −0.16 | −1.02 | −5.35 | 22.73 | 15 |
| 3.67 | 1.33 | −0.63 | −0.13 | −1.20 | −6.06 | 26.02 | 16 |
| 3.9 | 1.51 | −0.72 | −0.11 | −1.38 | −6.83 | 29.84 | 17 |
| 4.13 | 1.71 | −0.81 | −0.09 | −1.56 | −7.69 | 34.25 | 18 |
| 4.36 | 1.92 | −0.91 | −0.08 | −1.73 | −8.62 | 39.28 | 19 |
| 4.59 | 2.16 | −1.01 | −0.07 | −1.91 | −9.65 | 45.00 | 20 |
| 4.82 | 2.42 | −1.12 | −0.07 | −2.07 | −10.76 | 51.47 | 21 |
| 5.05 | 2.71 | −1.23 | −0.07 | −2.23 | −11.98 | 58.73 | 22 |
| 5.28 | 3.02 | −1.35 | −0.09 | −2.38 | −13.29 | 66.85 | 23 |
| 5.51 | 3.35 | −1.47 | −0.11 | −2.51 | −14.72 | 75.86 | 24 |
| 5.74 | 3.72 | −1.59 | −0.15 | −2.63 | −16.25 | 85.84 | 25 |
| 5.96 | 4.11 | −1.72 | −0.20 | −2.73 | −17.91 | 96.83 | 26 |
| 6.19 | 4.53 | −1.85 | −0.27 | −2.81 | −19.69 | 108.88 | 27 |
| 6.42 | 4.99 | −1.99 | −0.35 | −2.87 | −21.60 | 122.06 | 28 |
| 6.65 | 5.48 | −2.13 | −0.44 | −2.90 | −23.64 | 136.41 | 29 |
| 6.88 | 6.00 | −2.27 | −0.55 | −2.91 | −25.81 | 151.98 | 30 |

Table E-3: 5° degree yaw, single unit, free to heave, pitch, & roll

| $V_{model}$ [ft/s] | $F_x$ [lbs] | $F_y$ [lbs] | $F_z$ [lbs] | $M_x$ [in-lbs] | $M_y$ [in-lbs] | $M_z$ [in-lbs] | $V_{ship}$ [kts] |
|---|---|---|---|---|---|---|---|
| 2.29 | 0.68 | −0.67 | −0.95 | −0.83 | −3.44 | 32.53 | 10 |
| 2.52 | 0.77 | −0.80 | −0.92 | −1.17 | −3.81 | 34.39 | 11 |
| 2.75 | 0.87 | −0.95 | −0.88 | −1.56 | −4.22 | 36.84 | 12 |
| 2.98 | 0.98 | −1.11 | −0.84 | −1.99 | −4.69 | 40.12 | 13 |
| 3.21 | 1.11 | −1.29 | −0.78 | −2.45 | −5.21 | 44.43 | 14 |
| 3.44 | 1.26 | −1.49 | −0.73 | −2.94 | −5.81 | 50.01 | 15 |
| 3.67 | 1.44 | −1.71 | −0.67 | −3.47 | −6.49 | 57.05 | 16 |
| 3.9 | 1.64 | −1.95 | −0.62 | −4.01 | −7.26 | 65.80 | 17 |
| 4.13 | 1.87 | −2.22 | −0.58 | −4.59 | −8.13 | 76.46 | 18 |
| 4.36 | 2.13 | −2.50 | −0.55 | −5.19 | −9.11 | 89.25 | 19 |
| 4.59 | 2.42 | −2.81 | −0.53 | −5.80 | −10.21 | 104.39 | 20 |
| 4.82 | 2.75 | −3.14 | −0.52 | −6.44 | −11.45 | 122.11 | 21 |
| 5.05 | 3.11 | −3.50 | −0.54 | −7.09 | −12.82 | 142.61 | 22 |
| 5.28 | 3.51 | −3.88 | −0.57 | −7.75 | −14.35 | 166.12 | 23 |
| 5.51 | 3.96 | −4.30 | −0.63 | −8.43 | −16.03 | 192.86 | 24 |
| 5.74 | 4.45 | −4.74 | −0.72 | −9.11 | −17.89 | 223.05 | 25 |
| 5.96 | 4.99 | −5.20 | −0.84 | −9.79 | −19.92 | 256.89 | 26 |
| 6.19 | 5.58 | −5.70 | −0.99 | −10.48 | −22.14 | 294.63 | 27 |
| 6.42 | 6.22 | −6.24 | −1.18 | −11.18 | −24.57 | 336.46 | 28 |
| 6.65 | 6.91 | −6.80 | −1.40 | −11.86 | −27.20 | 382.62 | 29 |
| 6.88 | 7.67 | −7.40 | −1.67 | −12.55 | −30.05 | 433.31 | 30 |

Table E-4: 7.5° degree yaw, single unit, free to heave, pitch, & roll

| $V_{model}$ [ft/s] | $F_x$ [lbs] | $F_y$ [lbs] | $F_z$ [lbs] | $M_x$ [in-lbs] | $M_y$ [in-lbs] | $M_z$ [in-lbs] | $V_{ship}$ [kts] |
|---|---|---|---|---|---|---|---|
| 2.29 | 0.60 | −0.93 | −0.53 | −1.63 | −2.78 | 39.16 | 10 |
| 2.52 | 0.74 | −1.16 | −0.49 | −1.96 | −3.51 | 45.18 | 11 |
| 2.75 | 0.89 | −1.41 | −0.45 | −2.34 | −4.28 | 52.26 | 12 |
| 2.98 | 1.06 | −1.68 | −0.41 | −2.78 | −5.10 | 60.57 | 13 |
| 3.21 | 1.25 | −1.97 | −0.36 | −3.27 | −5.94 | 70.30 | 14 |
| 3.44 | 1.46 | −2.28 | −0.32 | −3.84 | −6.82 | 81.59 | 15 |
| 3.67 | 1.69 | −2.61 | −0.28 | −4.47 | −7.71 | 94.64 | 16 |
| 3.9 | 1.94 | −2.96 | −0.25 | −5.19 | −8.61 | 109.61 | 17 |
| 4.13 | 2.22 | −3.32 | −0.23 | −5.98 | −9.51 | 126.66 | 18 |
| 4.36 | 2.51 | −3.71 | −0.22 | −6.87 | −10.40 | 145.98 | 19 |
| 4.59 | 2.83 | −4.11 | −0.23 | −7.85 | −11.28 | 167.73 | 20 |
| 4.82 | 3.18 | −4.52 | −0.26 | −8.92 | −12.14 | 192.09 | 21 |
| 5.05 | 3.55 | −4.96 | −0.30 | −10.11 | −12.97 | 219.21 | 22 |
| 5.28 | 3.95 | −5.41 | −0.37 | −11.40 | −13.75 | 249.29 | 23 |
| 5.51 | 4.38 | −5.87 | −0.46 | −12.80 | −14.49 | 282.48 | 24 |
| 5.74 | 4.83 | −6.35 | −0.58 | −14.32 | −15.18 | 318.96 | 25 |

**Table E-5: 10° degree yaw, single unit, free to heave, pitch, & roll**

| $V_{model}$ [ft/s] | $F_x$ [lbs] | $F_y$ [lbs] | $F_z$ [lbs] | $M_x$ [in-lbs] | $M_y$ [in-lbs] | $M_z$ [in-lbs] | $V_{ship}$ [kts] |
|---|---|---|---|---|---|---|---|
| 2.29 | 0.75 | −1.23 | −0.68 | −2.71 | −3.17 | 56.21 | 10 |
| 2.52 | 0.91 | −1.47 | −0.68 | −3.18 | −3.57 | 68.98 | 11 |
| 2.75 | 1.08 | −1.75 | −0.68 | −3.73 | −3.99 | 83.33 | 12 |
| 2.98 | 1.29 | −2.06 | −0.67 | −4.36 | −4.42 | 99.34 | 13 |
| 3.21 | 1.51 | −2.42 | −0.68 | −5.08 | −4.85 | 117.08 | 14 |
| 3.44 | 1.77 | −2.83 | −0.68 | −5.91 | −5.30 | 136.63 | 15 |
| 3.67 | 2.06 | −3.29 | −0.70 | −6.85 | −5.75 | 158.05 | 16 |
| 3.9 | 2.38 | −3.80 | −0.74 | −7.91 | −6.21 | 181.42 | 17 |
| 4.13 | 2.74 | −4.36 | −0.78 | −9.10 | −6.67 | 206.82 | 18 |
| 4.36 | 3.14 | −4.99 | −0.85 | −10.44 | −7.14 | 234.30 | 19 |

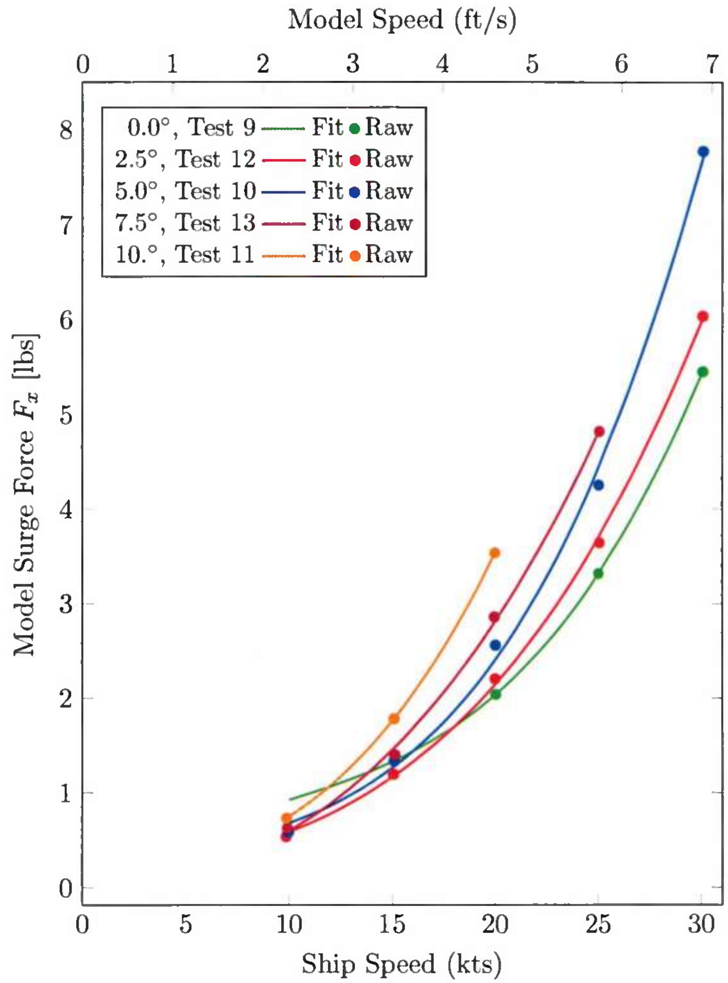



**Figure E-2: Surge force, single unit, free to heave, pitch, & roll**

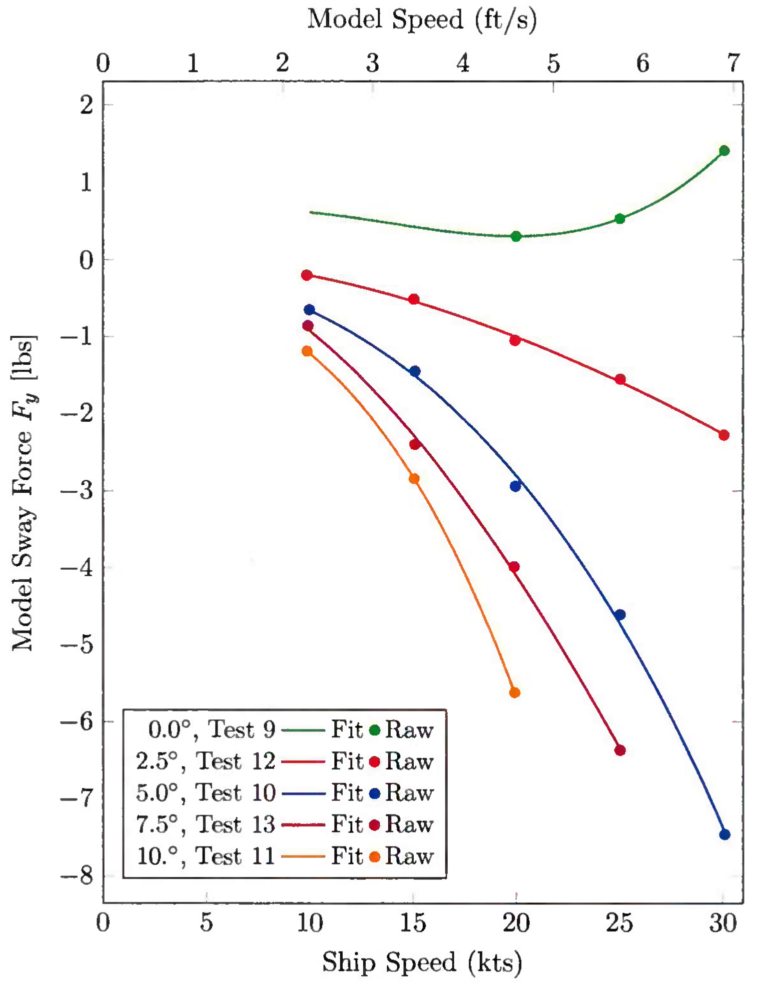



**Figure E-3: Sway force, single unit, free to heave, pitch, & roll**

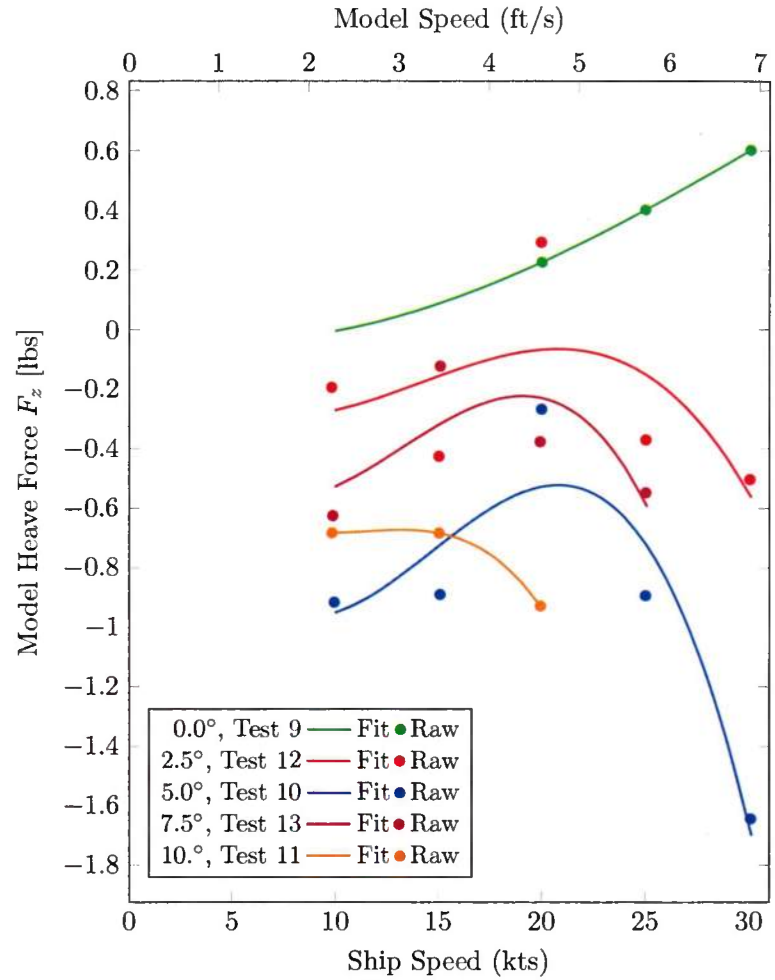



**Figure E-4: Heave force, single unit, free to heave, pitch, & roll**

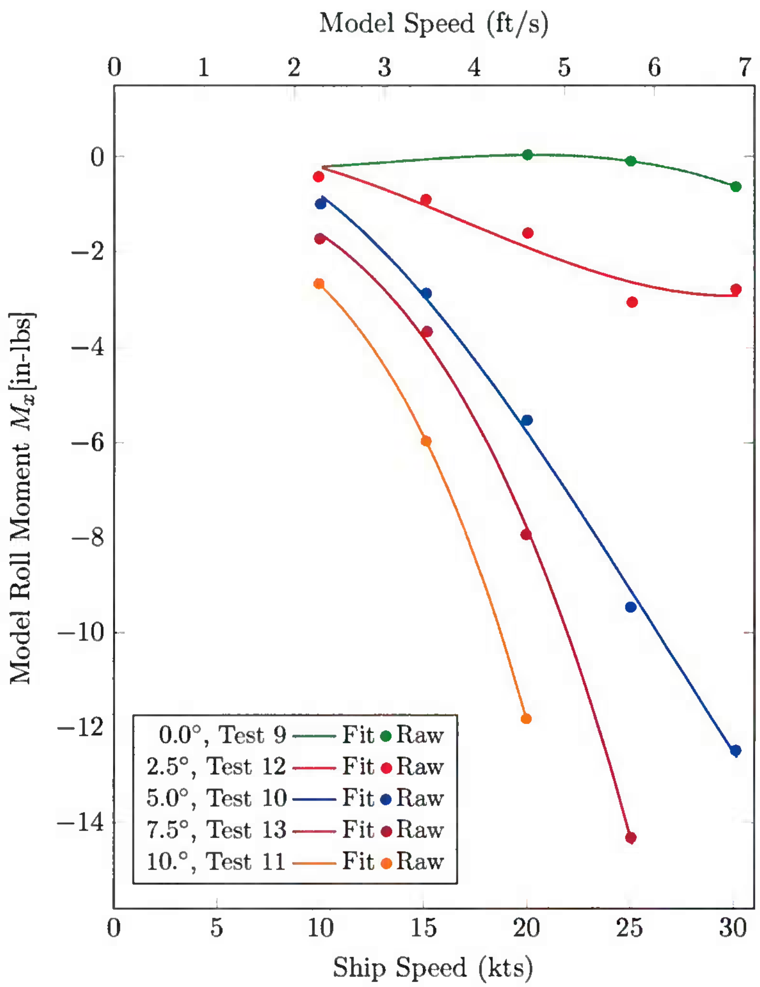



**Figure E-5: Roll moment, single unit, free to heave, pitch, & roll**

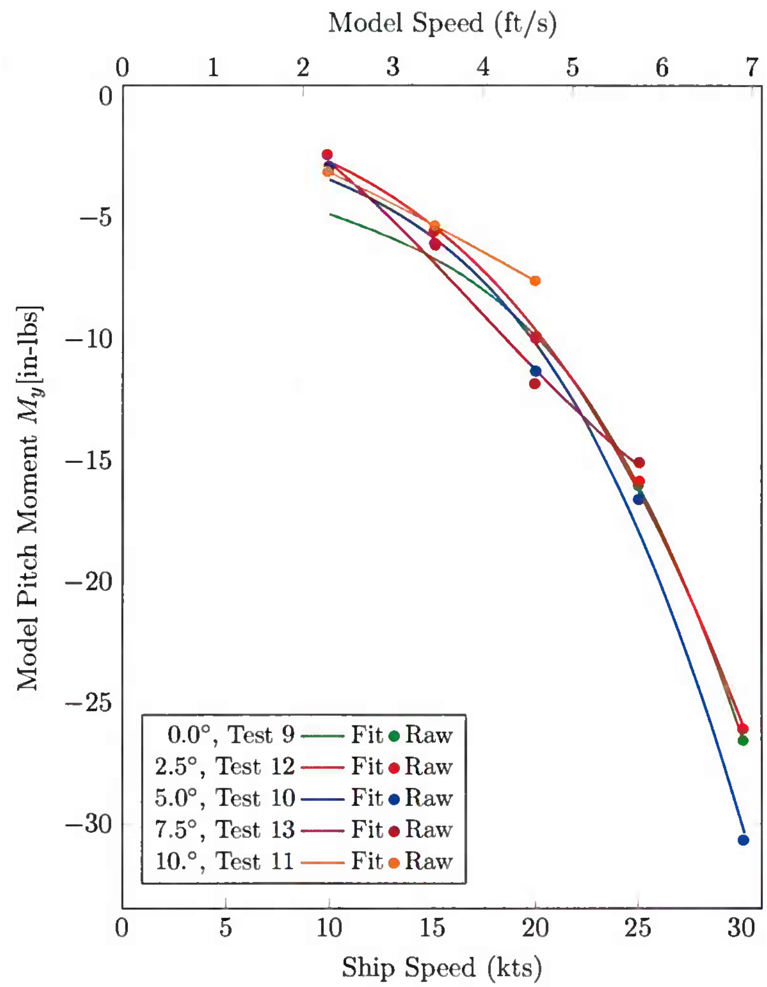



**Figure E-6: Pitch moment, single unit, free to heave, pitch, & roll**

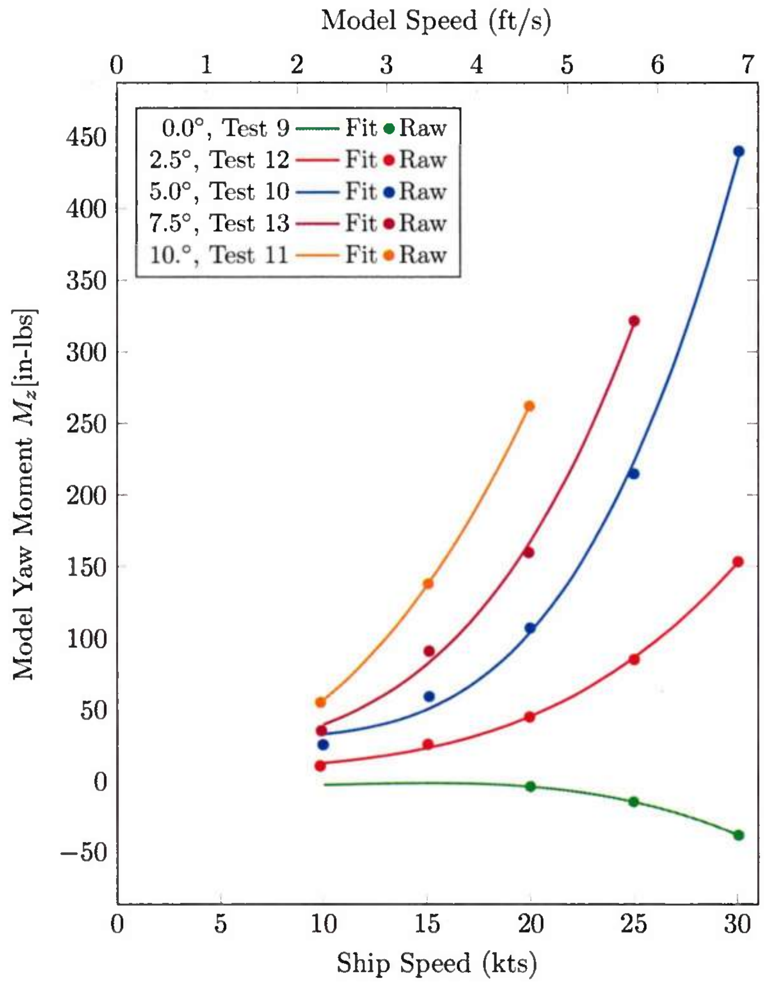



**Figure E-7: Yaw moment, single unit, free to heave, pitch, & roll**

## Single Unit, Rigid Mount, Fixed at Various Yaw Angles

**Table E-6:** 0° degree yaw, single unit, rigid mount

| $V_{model}$ [ft/s] | $F_x$ [lbs] | $F_y$ [lbs] | $F_z$ [lbs] | $M_x$ [in-lbs] | $M_y$ [in-lbs] | $M_z$ [in-lbs] | $V_{ship}$ [kts] |
|---|---|---|---|---|---|---|---|
| 2.29 | 1.32 | −1.10 | 40.41 | −3.04 | 17.52 | 5.10 | 10 |
| 2.52 | 1.43 | −1.21 | 40.87 | −2.85 | 13.12 | 5.60 | 11 |
| 2.75 | 1.53 | −1.32 | 40.87 | −2.62 | 8.52 | 6.13 | 12 |
| 2.98 | 1.63 | −1.43 | 40.46 | −2.35 | 3.92 | 6.69 | 13 |
| 3.21 | 1.74 | −1.53 | 39.69 | −2.06 | −0.45 | 7.31 | 14 |
| 3.44 | 1.85 | −1.63 | 38.61 | −1.75 | −4.36 | 7.99 | 15 |
| 3.67 | 1.96 | −1.72 | 37.26 | −1.44 | −7.58 | 8.73 | 16 |
| 3.9 | 2.08 | −1.81 | 35.69 | −1.14 | −9.89 | 9.54 | 17 |
| 4.13 | 2.21 | −1.90 | 33.95 | −0.87 | −11.07 | 10.44 | 18 |
| 4.36 | 2.34 | −1.98 | 32.10 | −0.62 | −10.88 | 11.43 | 19 |
| 4.59 | 2.48 | −2.05 | 30.17 | −0.41 | −9.11 | 12.52 | 20 |
| 4.82 | 2.64 | −2.11 | 28.22 | −0.26 | −5.53 | 13.72 | 21 |
| 5.05 | 2.80 | −2.17 | 26.29 | −0.17 | 0.09 | 15.03 | 22 |
| 5.28 | 2.98 | −2.22 | 24.43 | −0.15 | 7.97 | 16.47 | 23 |
| 5.51 | 3.17 | −2.26 | 22.69 | −0.22 | 18.34 | 18.05 | 24 |
| 5.74 | 3.37 | −2.29 | 21.12 | −0.38 | 31.42 | 19.76 | 25 |
| 5.96 | 3.59 | −2.31 | 19.77 | −0.65 | 47.44 | 21.63 | 26 |
| 6.19 | 3.83 | −2.32 | 18.68 | −1.04 | 66.63 | 23.66 | 27 |
| 6.42 | 4.08 | −2.32 | 17.90 | −1.56 | 89.20 | 25.86 | 28 |
| 6.65 | 4.36 | −2.30 | 17.49 | −2.22 | 115.39 | 28.23 | 29 |
| 6.88 | 4.65 | −2.28 | 17.48 | −3.03 | 145.42 | 30.79 | 30 |

**Table E-7:** 5° degree yaw, single unit, rigid mount

| $V_{model}$ [ft/s] | $F_x$ [lbs] | $F_y$ [lbs] | $F_z$ [lbs] | $M_x$ [in-lbs] | $M_y$ [in-lbs] | $M_z$ [in-lbs] | $V_{ship}$ [kts] |
|---|---|---|---|---|---|---|---|
| 2.29 | −0.08 | 0.30 | −20.33 | 3.21 | 5.83 | −16.60 | 10 |
| 2.52 | 0.02 | 0.35 | −19.83 | 3.26 | 4.50 | −19.87 | 11 |
| 2.75 | 0.14 | 0.41 | −19.14 | 3.30 | 3.18 | −23.58 | 12 |
| 2.98 | 0.27 | 0.47 | −18.34 | 3.34 | 1.97 | −27.74 | 13 |
| 3.21 | 0.42 | 0.54 | −17.50 | 3.39 | 0.94 | −32.39 | 14 |
| 3.44 | 0.59 | 0.62 | −16.70 | 3.46 | 0.21 | −37.57 | 15 |
| 3.67 | 0.76 | 0.70 | −15.99 | 3.57 | −0.15 | −43.31 | 16 |
| 3.9 | 0.95 | 0.78 | −15.46 | 3.72 | −0.04 | −49.64 | 17 |
| 4.13 | 1.16 | 0.87 | −15.17 | 3.92 | 0.62 | −56.60 | 18 |
| 4.36 | 1.37 | 0.97 | −15.19 | 4.18 | 1.94 | −64.21 | 19 |
| 4.59 | 1.59 | 1.07 | −15.59 | 4.52 | 3.99 | −72.52 | 20 |
| 4.82 | 1.83 | 1.18 | −16.45 | 4.93 | 6.87 | −81.56 | 21 |
| 5.05 | 2.07 | 1.29 | −17.84 | 5.44 | 10.67 | −91.35 | 22 |
| 5.28 | 2.32 | 1.41 | −19.82 | 6.06 | 15.49 | −101.93 | 23 |
| 5.51 | 2.58 | 1.54 | −22.46 | 6.78 | 21.41 | −113.34 | 24 |
| 5.74 | 2.84 | 1.67 | −25.84 | 7.63 | 28.52 | −125.61 | 25 |

**Table E-8:** 10° degree yaw, single unit, rigid mount

| $V_{model}$ [ft/s] | $F_x$ [lbs] | $F_y$ [lbs] | $F_z$ [lbs] | $M_x$ [in-lbs] | $M_y$ [in-lbs] | $M_z$ [in-lbs] | $V_{ship}$ [kts] |
|---|---|---|---|---|---|---|---|
| 2.29 | 0.83 | 1.14 | −6.80 | 2.61 | −5.27 | −48.30 | 10 |
| 2.52 | 0.95 | 1.27 | −7.22 | 3.20 | −5.53 | −58.25 | 11 |
| 2.75 | 1.08 | 1.44 | −7.67 | 3.79 | −5.94 | −69.35 | 12 |
| 2.98 | 1.24 | 1.65 | −8.19 | 4.35 | −6.56 | −81.63 | 13 |
| 3.21 | 1.42 | 1.90 | −8.80 | 4.86 | −7.43 | −95.15 | 14 |
| 3.44 | 1.63 | 2.20 | −9.51 | 5.32 | −8.62 | −109.96 | 15 |
| 3.67 | 1.87 | 2.56 | −10.36 | 5.70 | −10.16 | −126.12 | 16 |
| 3.9 | 2.15 | 2.98 | −11.35 | 5.98 | −12.11 | −143.66 | 17 |
| 4.13 | 2.46 | 3.48 | −12.53 | 6.16 | −14.53 | −162.66 | 18 |
| 4.36 | 2.82 | 4.05 | −13.90 | 6.21 | −17.45 | −183.14 | 19 |

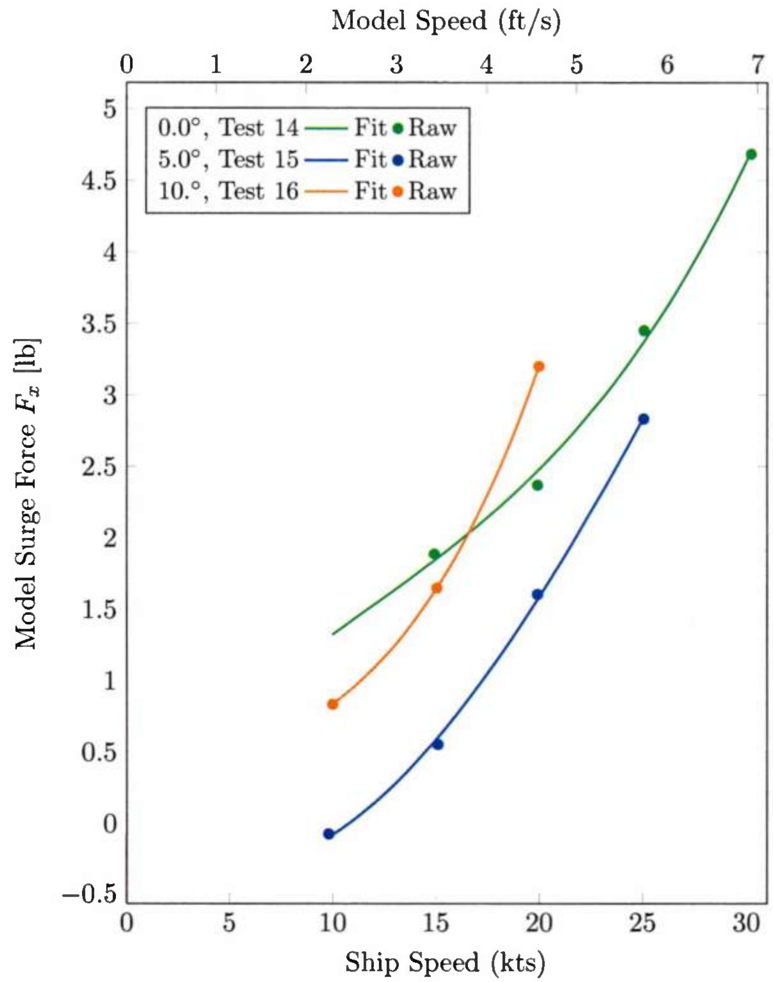



**Figure E-8:** Surge force, single unit, rigid mount

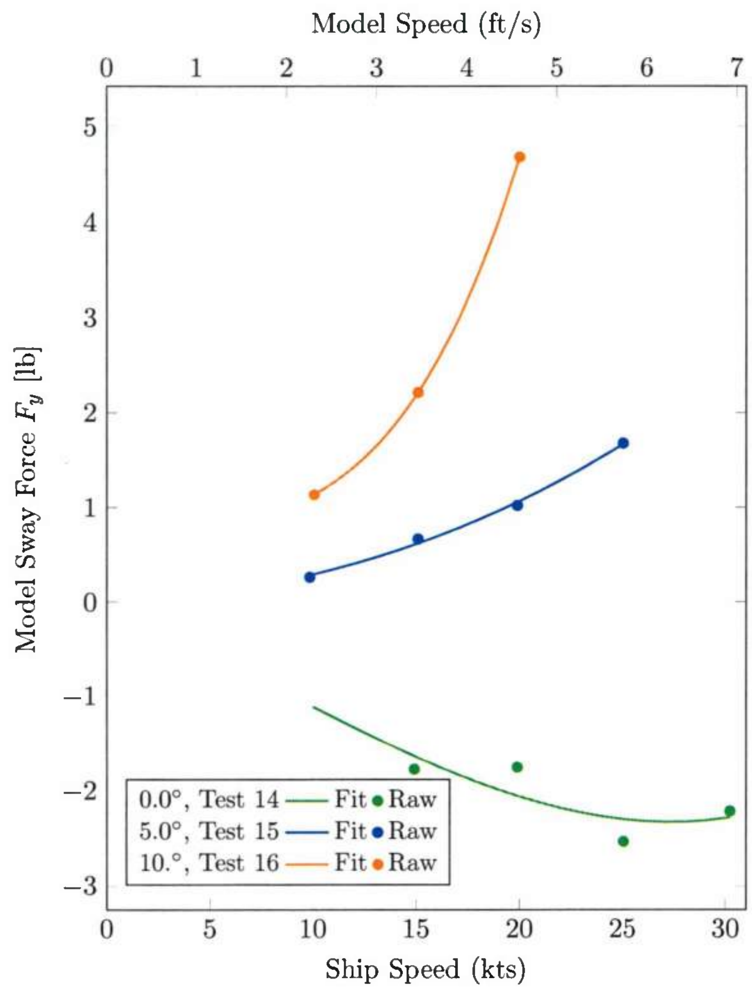



Figure E-9: Sway force, single unit, rigid mount

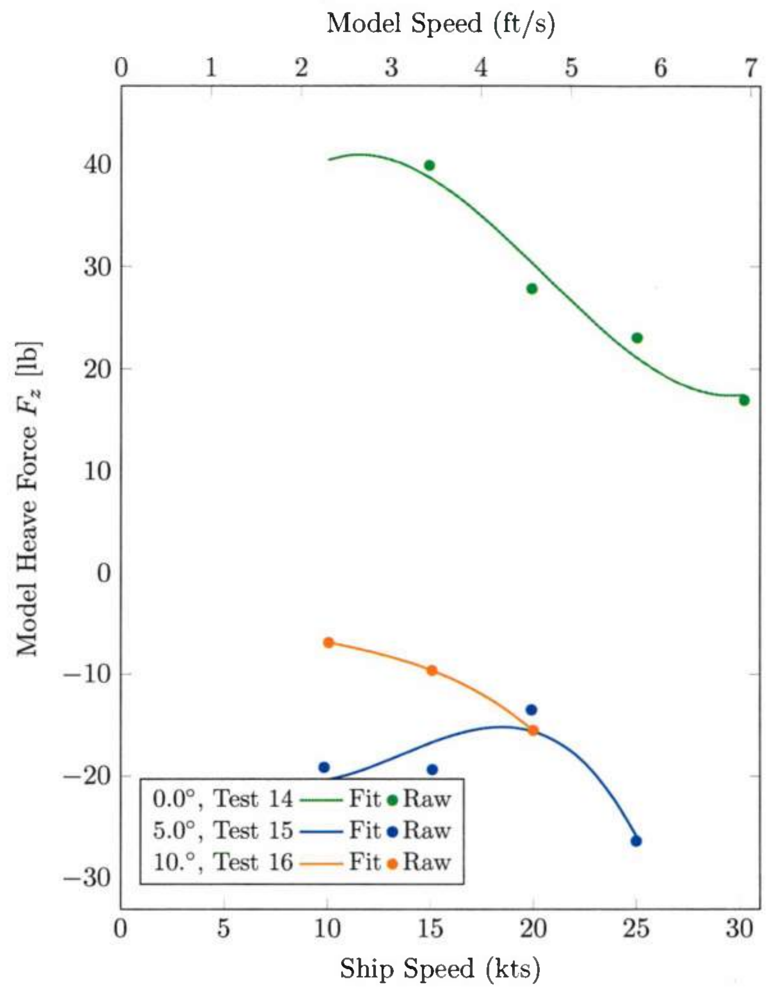



Figure E-10: Heave force, single unit, rigid mount

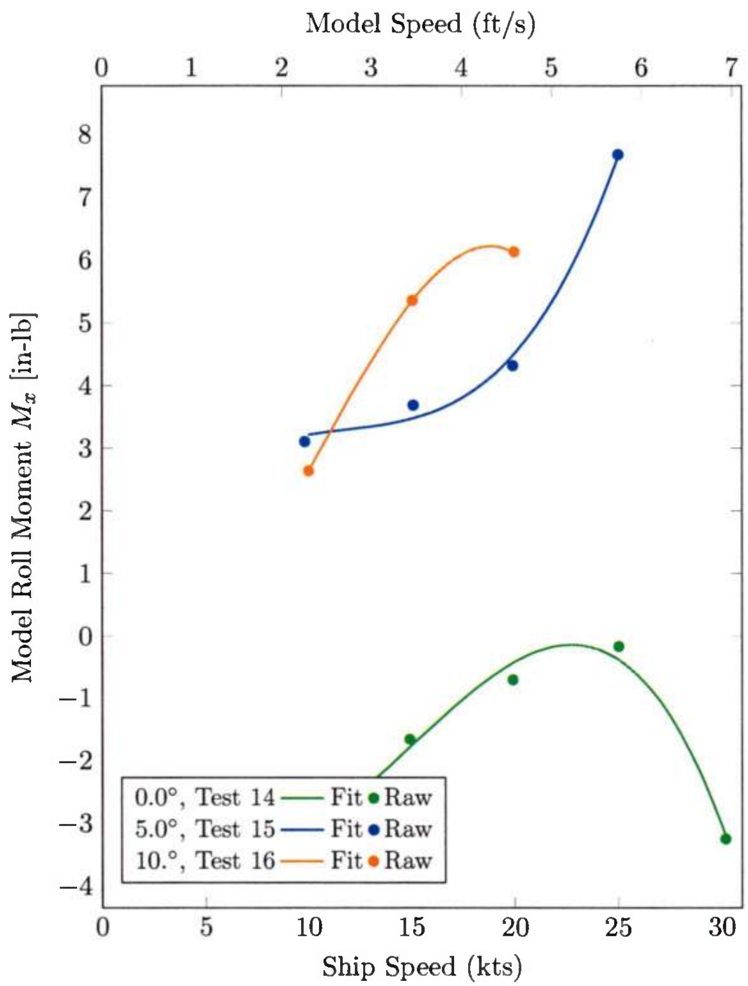



**Figure E-11: Roll moment, single unit, rigid mount**

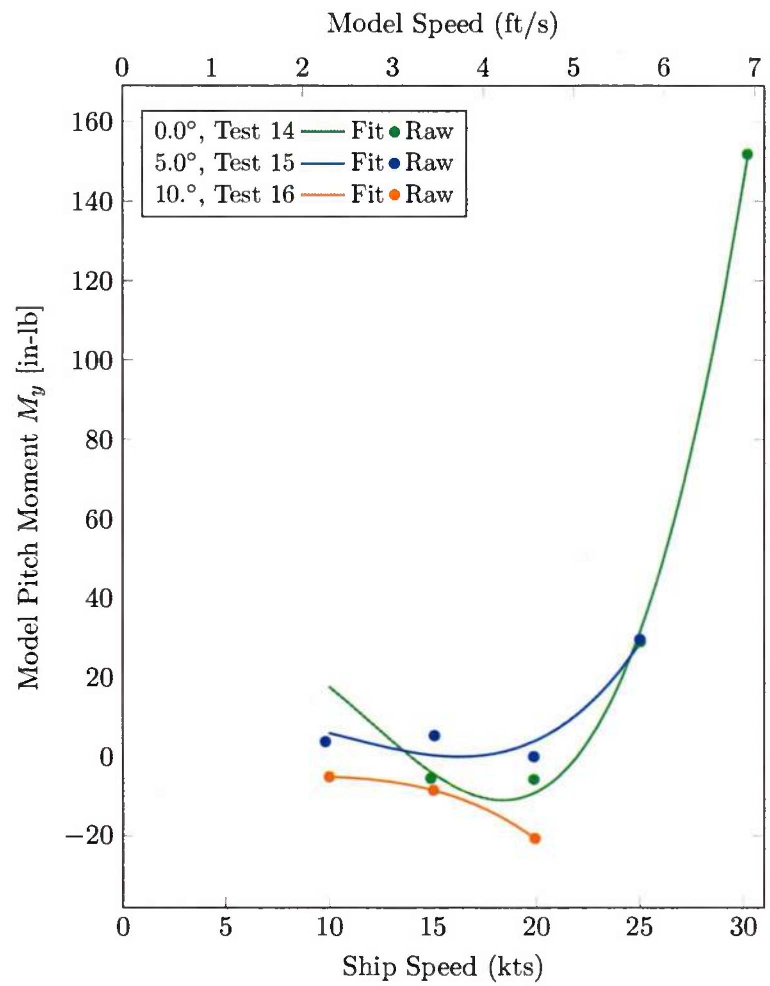



**Figure E-12: Pitch moment, single unit, rigid mount**

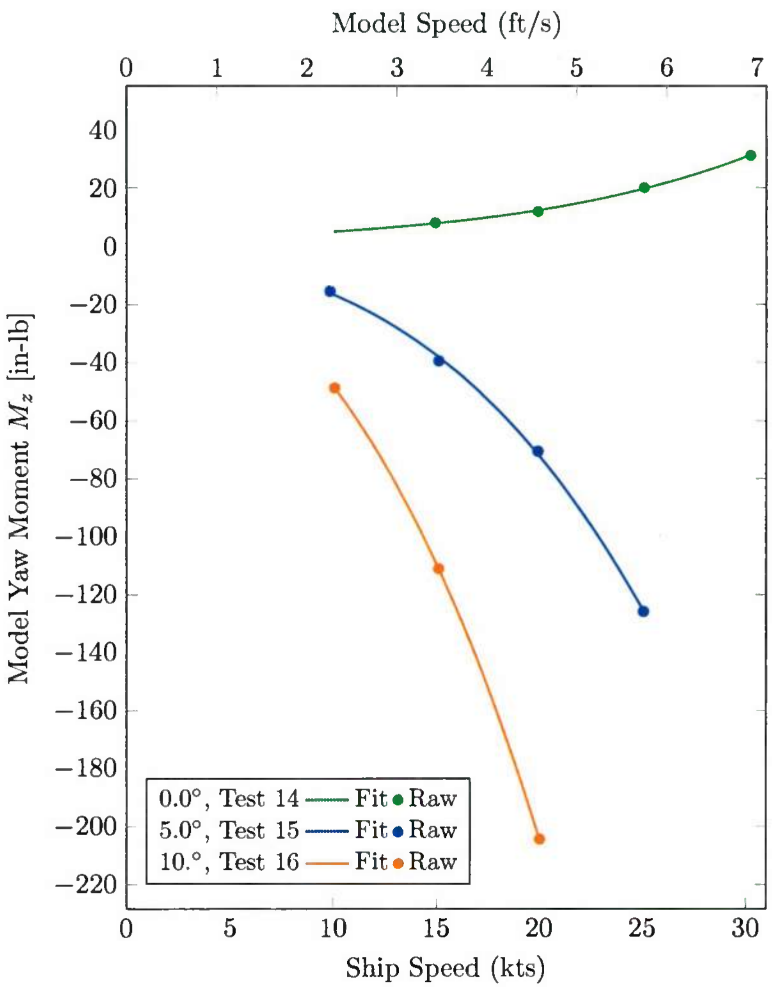



**Figure E-13: Yaw moment, single unit, rigid mount**

## Single Unit, Rigid Mount, Rudder Fixed at Non-Zero Angles

Table E-9: Surge force, varied rudder angle, single unit, rigid mount

| $V_{model}$ [ft/s] | 0° [in] | 5° [in] | 10° [in] | 20° [in] | 30° [in] | $V_{ship}$ [kts] |
|---|---|---|---|---|---|---|
| 2.2 | 0.42 | 0.40 | 0.40 | 0.45 | 0.58 | 9.6 |
| 2.4 | 0.49 | 0.47 | 0.47 | 0.54 | 0.67 | 10.3 |
| 2.5 | 0.57 | 0.54 | 0.55 | 0.62 | 0.78 | 11.0 |
| 2.7 | 0.65 | 0.62 | 0.63 | 0.72 | 0.89 | 11.8 |
| 2.9 | 0.73 | 0.71 | 0.72 | 0.82 | 1.01 | 12.5 |
| 3.0 | 0.82 | 0.80 | 0.81 | 0.93 | 1.13 | 13.2 |
| 3.2 | 0.92 | 0.90 | 0.91 | 1.04 | 1.27 | 14.0 |
| 3.4 | 1.02 | 1.00 | 1.01 | 1.16 | 1.41 | 14.7 |
| 3.5 | 1.12 | 1.11 | 1.12 | 1.29 | 1.55 | 15.5 |
| 3.7 | 1.24 | 1.22 | 1.24 | 1.42 | 1.71 | 16.2 |
| 3.9 | 1.35 | 1.34 | 1.36 | 1.56 | 1.87 | 16.9 |
| 4.1 | 1.47 | 1.46 | 1.49 | 1.71 | 2.04 | 17.7 |
| 4.2 | 1.60 | 1.59 | 1.62 | 1.86 | 2.22 | 18.4 |
| 4.4 | 1.73 | 1.73 | 1.76 | 2.02 | 2.40 | 19.1 |
| 4.6 | 1.87 | 1.87 | 1.90 | 2.19 | 2.60 | 19.9 |
| 4.7 | 2.02 | 2.01 | 2.05 | 2.36 | 2.80 | 20.6 |
| 4.9 | 2.16 | 2.16 | 2.21 | 2.54 | 3.00 | 21.3 |
| 5.1 | 2.32 | 2.32 | 2.37 | 2.73 | 3.22 | 22.1 |
| 5.2 | 2.48 | 2.48 | 2.54 | 2.92 | 3.44 | 22.8 |
| 5.4 | 2.64 | 2.65 | 2.71 | 3.12 | 3.67 | 23.5 |
| 5.6 | 2.81 | 2.82 | 2.89 | 3.32 | 3.91 | 24.3 |
| 5.7 | 2.98 | 3.00 | 3.07 | 3.54 | 4.15 | 25.0 |
| 5.9 | 3.16 | 3.19 | 3.26 | 3.76 | 4.40 | 25.8 |
| 6.1 | 3.35 | 3.38 | 3.45 | 3.98 | 4.66 | 26.5 |
| 6.2 | 3.54 | 3.57 | 3.66 | 4.21 | 4.93 | 27.2 |
| 6.4 | 3.74 | 3.77 | 3.86 | 4.45 | 5.20 | 28.0 |
| 6.6 | 3.94 | 3.98 | 4.07 | 4.70 | 5.48 | 28.7 |
| 6.8 | 4.14 | 4.19 | 4.29 | 4.95 | 5.77 | 29.4 |
| 6.9 | 4.31 | 4.37 | 4.47 | 5.15 | 6.01 | 30.0 |

Table E-10: Sway force, varied rudder angle, single unit, rigid mount

| $V_{model}$ [ft/s] | 0° [in] | 5° [in] | 10° [in] | 20° [in] | 30° [in] | $V_{ship}$ [kts] |
|---|---|---|---|---|---|---|
| 2.2 | −0.08 | −0.11 | −0.23 | −0.39 | −0.45 | 9.6 |
| 2.4 | −0.09 | −0.12 | −0.26 | −0.43 | −0.50 | 10.3 |
| 2.5 | −0.09 | −0.14 | −0.29 | −0.48 | −0.55 | 11.0 |
| 2.7 | −0.10 | −0.15 | −0.32 | −0.54 | −0.61 | 11.8 |
| 2.9 | −0.10 | −0.17 | −0.36 | −0.59 | −0.67 | 12.5 |
| 3.0 | −0.10 | −0.18 | −0.39 | −0.65 | −0.73 | 13.2 |
| 3.2 | −0.11 | −0.20 | −0.43 | −0.72 | −0.79 | 14.0 |
| 3.4 | −0.11 | −0.22 | −0.47 | −0.78 | −0.86 | 14.7 |
| 3.5 | −0.11 | −0.23 | −0.50 | −0.85 | −0.93 | 15.5 |
| 3.7 | −0.11 | −0.25 | −0.55 | −0.92 | −1.00 | 16.2 |
| 3.9 | −0.11 | −0.27 | −0.59 | −0.99 | −1.07 | 16.9 |
| 4.1 | −0.12 | −0.29 | −0.63 | −1.07 | −1.14 | 17.7 |
| 4.2 | −0.12 | −0.31 | −0.68 | −1.14 | −1.22 | 18.4 |
| 4.4 | −0.12 | −0.33 | −0.73 | −1.22 | −1.30 | 19.1 |
| 4.6 | −0.12 | −0.36 | −0.77 | −1.31 | −1.38 | 19.9 |
| 4.7 | −0.12 | −0.38 | −0.83 | −1.39 | −1.47 | 20.6 |
| 4.9 | −0.12 | −0.40 | −0.88 | −1.48 | −1.56 | 21.3 |
| 5.1 | −0.12 | −0.43 | −0.93 | −1.57 | −1.65 | 22.1 |
| 5.2 | −0.12 | −0.45 | −0.99 | −1.67 | −1.74 | 22.8 |
| 5.4 | −0.12 | −0.48 | −1.04 | −1.77 | −1.83 | 23.5 |
| 5.6 | −0.11 | −0.51 | −1.10 | −1.87 | −1.93 | 24.3 |
| 5.7 | −0.11 | −0.53 | −1.16 | −1.97 | −2.03 | 25.0 |
| 5.9 | −0.11 | −0.56 | −1.22 | −2.07 | −2.13 | 25.8 |
| 6.1 | −0.11 | −0.59 | −1.28 | −2.18 | −2.24 | 26.5 |
| 6.2 | −0.11 | −0.62 | −1.35 | −2.29 | −2.34 | 27.2 |
| 6.4 | −0.10 | −0.65 | −1.41 | −2.40 | −2.45 | 28.0 |
| 6.6 | −0.10 | −0.68 | −1.48 | −2.52 | −2.56 | 28.7 |
| 6.8 | −0.10 | −0.71 | −1.55 | −2.64 | −2.68 | 29.4 |
| 6.9 | −0.09 | −0.74 | −1.62 | −2.76 | −2.80 | 30.0 |

Table E-11: Heave force, varied rudder angle, single unit, rigid mount

| $V_{model}$ [ft/s] | 0° [in] | 5° [in] | 10° [in] | 20° [in] | 30° [in] | $V_{ship}$ [kts] |
|---|---|---|---|---|---|---|
| 2.2 | −1.17 | −1.63 | −2.38 | −2.48 | −2.30 | 9.6 |
| 2.4 | −1.37 | −1.84 | −2.62 | −2.74 | −2.52 | 10.3 |
| 2.5 | −1.58 | −2.07 | −2.88 | −3.00 | −2.76 | 11.0 |
| 2.7 | −1.81 | −2.31 | −3.14 | −3.26 | −3.00 | 11.8 |
| 2.9 | −2.05 | −2.56 | −3.42 | −3.54 | −3.25 | 12.5 |
| 3.0 | −2.31 | −2.83 | −3.70 | −3.83 | −3.50 | 13.2 |
| 3.2 | −2.58 | −3.11 | −3.99 | −4.12 | −3.77 | 14.0 |
| 3.4 | −2.87 | −3.40 | −4.29 | −4.42 | −4.04 | 14.7 |
| 3.5 | −3.18 | −3.70 | −4.60 | −4.74 | −4.31 | 15.5 |
| 3.7 | −3.50 | −4.02 | −4.92 | −5.06 | −4.60 | 16.2 |
| 3.9 | −3.83 | −4.35 | −5.25 | −5.39 | −4.89 | 16.9 |
| 4.1 | −4.18 | −4.69 | −5.59 | −5.72 | −5.19 | 17.7 |
| 4.2 | −4.55 | −5.05 | −5.93 | −6.07 | −5.50 | 18.4 |
| 4.4 | −4.93 | −5.42 | −6.29 | −6.42 | −5.81 | 19.1 |
| 4.6 | −5.32 | −5.80 | −6.65 | −6.79 | −6.13 | 19.9 |
| 4.7 | −5.74 | −6.19 | −7.02 | −7.16 | −6.46 | 20.6 |
| 4.9 | −6.16 | −6.60 | −7.41 | −7.54 | −6.80 | 21.3 |
| 5.1 | −6.60 | −7.02 | −7.80 | −7.93 | −7.14 | 22.1 |
| 5.2 | −7.06 | −7.45 | −8.20 | −8.33 | −7.49 | 22.8 |
| 5.4 | −7.53 | −7.89 | −8.61 | −8.73 | −7.85 | 23.5 |
| 5.6 | −8.02 | −8.35 | −9.02 | −9.15 | −8.21 | 24.3 |
| 5.7 | −8.52 | −8.82 | −9.45 | −9.57 | −8.58 | 25.0 |
| 5.9 | −9.04 | −9.31 | −9.89 | −10.00 | −8.96 | 25.8 |
| 6.1 | −9.58 | −9.80 | −10.33 | −10.44 | −9.35 | 26.5 |
| 6.2 | −10.12 | −10.31 | −10.79 | −10.89 | −9.74 | 27.2 |
| 6.4 | −10.69 | −10.83 | −11.25 | −11.35 | −10.14 | 28.0 |
| 6.6 | −11.27 | −11.37 | −11.73 | −11.82 | −10.55 | 28.7 |
| 6.8 | −11.86 | −11.92 | −12.21 | −12.29 | −10.96 | 29.4 |
| 6.9 | −12.47 | −12.48 | −12.70 | −12.78 | −11.39 | 30.0 |

Table E-12: Roll moment, varied rudder angle, single unit, rigid mount

| $V_{model}$ [ft/s] | 0° [in-lb] | 5° [in-lb] | 10° [in-lb] | 20° [in-lb] | 30° [in-lb] | $V_{ship}$ [kts] |
|---|---|---|---|---|---|---|
| 2.2 | 0.35 | 0.19 | −0.06 | −0.23 | −0.82 | 9.6 |
| 2.4 | 0.32 | 0.15 | −0.14 | −0.32 | −0.88 | 10.3 |
| 2.5 | 0.28 | 0.10 | −0.22 | −0.42 | −0.93 | 11.0 |
| 2.7 | 0.24 | 0.04 | −0.31 | −0.53 | −0.98 | 11.8 |
| 2.9 | 0.18 | −0.03 | −0.41 | −0.65 | −1.04 | 12.5 |
| 3.0 | 0.12 | −0.11 | −0.52 | −0.78 | −1.09 | 13.2 |
| 3.2 | 0.05 | −0.20 | −0.64 | −0.93 | −1.14 | 14.0 |
| 3.4 | −0.02 | −0.29 | −0.77 | −1.08 | −1.19 | 14.7 |
| 3.5 | −0.11 | −0.40 | −0.91 | −1.25 | −1.24 | 15.5 |
| 3.7 | −0.20 | −0.51 | −1.06 | −1.42 | −1.29 | 16.2 |
| 3.9 | −0.31 | −0.63 | −1.22 | −1.61 | −1.34 | 16.9 |
| 4.1 | −0.42 | −0.76 | −1.39 | −1.80 | −1.38 | 17.7 |
| 4.2 | −0.53 | −0.89 | −1.57 | −2.01 | −1.43 | 18.4 |
| 4.4 | −0.66 | −1.04 | −1.75 | −2.23 | −1.47 | 19.1 |
| 4.6 | −0.79 | −1.19 | −1.95 | −2.45 | −1.52 | 19.9 |
| 4.7 | −0.94 | −1.35 | −2.16 | −2.69 | −1.56 | 20.6 |
| 4.9 | −1.09 | −1.52 | −2.38 | −2.94 | −1.60 | 21.3 |
| 5.1 | −1.25 | −1.70 | −2.60 | −3.20 | −1.64 | 22.1 |
| 5.2 | −1.41 | −1.89 | −2.84 | −3.47 | −1.68 | 22.8 |
| 5.4 | −1.59 | −2.09 | −3.08 | −3.75 | −1.72 | 23.5 |
| 5.6 | −1.77 | −2.29 | −3.34 | −4.04 | −1.76 | 24.3 |
| 5.7 | −1.96 | −2.50 | −3.60 | −4.34 | −1.79 | 25.0 |
| 5.9 | −2.16 | −2.73 | −3.88 | −4.65 | −1.83 | 25.8 |
| 6.1 | −2.36 | −2.96 | −4.16 | −4.97 | −1.86 | 26.5 |
| 6.2 | −2.58 | −3.19 | −4.46 | −5.30 | −1.90 | 27.2 |
| 6.4 | −2.80 | −3.44 | −4.76 | −5.65 | −1.93 | 28.0 |
| 6.6 | −3.03 | −3.70 | −5.07 | −6.00 | −1.96 | 28.7 |
| 6.8 | −3.27 | −3.96 | −5.39 | −6.36 | −1.99 | 29.4 |
| 6.9 | −3.52 | −4.23 | −5.73 | −6.74 | −2.02 | 30.0 |

Table E-13: Pitch moment, varied rudder angle, single unit, rigid mount

| $V_{model}$ [ft/s] | 0° [in-lb] | 5° [in-lb] | 10° [in-lb] | 20° [in-lb] | 30° [in-lb] | $V_{ship}$ [kts] |
|---|---|---|---|---|---|---|
| 2.2 | −22.45 | −24.19 | −24.28 | −23.57 | −22.20 | 9.6 |
| 2.4 | −21.29 | −22.97 | −23.08 | −22.40 | −21.16 | 10.3 |
| 2.5 | −19.72 | −21.31 | −21.45 | −20.81 | −19.74 | 11.0 |
| 2.7 | −17.73 | −19.20 | −19.37 | −18.79 | −17.92 | 11.8 |
| 2.9 | −15.34 | −16.66 | −16.86 | −16.34 | −15.71 | 12.5 |
| 3.0 | −12.53 | −13.67 | −13.91 | −13.47 | −13.10 | 13.2 |
| 3.2 | −9.31 | −10.24 | −10.52 | −10.17 | −10.11 | 14.0 |
| 3.4 | −5.68 | −6.38 | −6.69 | −6.45 | −6.72 | 14.7 |
| 3.5 | −1.63 | −2.07 | −2.43 | −2.30 | −2.94 | 15.5 |
| 3.7 | 2.82 | 2.68 | 2.27 | 2.28 | 1.23 | 16.2 |
| 3.9 | 7.69 | 7.87 | 7.41 | 7.28 | 5.80 | 16.9 |
| 4.1 | 12.97 | 13.50 | 12.99 | 12.70 | 10.75 | 17.7 |
| 4.2 | 18.67 | 19.57 | 19.01 | 18.56 | 16.10 | 18.4 |
| 4.4 | 24.77 | 26.08 | 25.46 | 24.83 | 21.84 | 19.1 |
| 4.6 | 31.29 | 33.04 | 32.36 | 31.54 | 27.97 | 19.9 |
| 4.7 | 38.22 | 40.43 | 39.69 | 38.67 | 34.50 | 20.6 |
| 4.9 | 45.56 | 48.26 | 47.46 | 46.22 | 41.41 | 21.3 |
| 5.1 | 53.31 | 56.53 | 55.66 | 54.21 | 48.72 | 22.1 |
| 5.2 | 61.48 | 65.25 | 64.31 | 62.61 | 56.42 | 22.8 |
| 5.4 | 70.06 | 74.40 | 73.39 | 71.45 | 64.51 | 23.5 |
| 5.6 | 79.05 | 84.00 | 82.91 | 80.71 | 72.99 | 24.3 |
| 5.7 | 88.45 | 94.04 | 92.87 | 90.39 | 81.87 | 25.0 |
| 5.9 | 98.27 | 104.51 | 103.27 | 100.50 | 91.14 | 25.8 |
| 6.1 | 108.49 | 115.43 | 114.11 | 111.04 | 100.80 | 26.5 |
| 6.2 | 119.13 | 126.79 | 125.38 | 122.00 | 110.85 | 27.2 |
| 6.4 | 130.18 | 138.59 | 137.09 | 133.39 | 121.29 | 28.0 |
| 6.6 | 141.65 | 150.83 | 149.24 | 145.21 | 132.12 | 28.7 |
| 6.8 | 153.52 | 163.51 | 161.83 | 157.45 | 143.35 | 29.4 |
| 6.9 | 165.81 | 176.63 | 174.85 | 170.11 | 154.97 | 30.0 |

Table E-14: Yaw moment, varied rudder angle, single unit, rigid mount

| $V_{model}$ [ft/s] | 0° [in-lb] | 5° [in-lb] | 10° [in-lb] | 20° [in-lb] | 30° [in-lb] | $V_{ship}$ [kts] |
|---|---|---|---|---|---|---|
| 2.2 | 4.89 | 4.00 | 6.91 | 16.37 | 12.37 | 9.6 |
| 2.4 | 5.27 | 4.58 | 8.04 | 18.48 | 14.77 | 10.3 |
| 2.5 | 5.65 | 5.20 | 9.25 | 20.72 | 17.38 | 11.0 |
| 2.7 | 6.04 | 5.85 | 10.55 | 23.07 | 20.19 | 11.8 |
| 2.9 | 6.42 | 6.55 | 11.93 | 25.55 | 23.21 | 12.5 |
| 3.0 | 6.80 | 7.28 | 13.40 | 28.15 | 26.43 | 13.2 |
| 3.2 | 7.18 | 8.05 | 14.96 | 30.87 | 29.86 | 14.0 |
| 3.4 | 7.57 | 8.86 | 16.60 | 33.71 | 33.50 | 14.7 |
| 3.5 | 7.95 | 9.71 | 18.32 | 36.68 | 37.35 | 15.5 |
| 3.7 | 8.34 | 10.59 | 20.13 | 39.76 | 41.40 | 16.2 |
| 3.9 | 8.72 | 11.52 | 22.03 | 42.97 | 45.66 | 16.9 |
| 4.1 | 9.11 | 12.48 | 24.01 | 46.30 | 50.12 | 17.7 |
| 4.2 | 9.50 | 13.49 | 26.07 | 49.75 | 54.80 | 18.4 |
| 4.4 | 9.88 | 14.53 | 28.22 | 53.32 | 59.68 | 19.1 |
| 4.6 | 10.27 | 15.61 | 30.46 | 57.02 | 64.76 | 19.9 |
| 4.7 | 10.66 | 16.73 | 32.78 | 60.83 | 70.05 | 20.6 |
| 4.9 | 11.05 | 17.88 | 35.19 | 64.77 | 75.55 | 21.3 |
| 5.1 | 11.44 | 19.08 | 37.68 | 68.83 | 81.26 | 22.1 |
| 5.2 | 11.83 | 20.31 | 40.25 | 73.01 | 87.17 | 22.8 |
| 5.4 | 12.22 | 21.59 | 42.92 | 77.32 | 93.29 | 23.5 |
| 5.6 | 12.61 | 22.90 | 45.66 | 81.74 | 99.61 | 24.3 |
| 5.7 | 13.00 | 24.25 | 48.50 | 86.29 | 106.15 | 25.0 |
| 5.9 | 13.39 | 25.64 | 51.41 | 90.96 | 112.88 | 25.8 |
| 6.1 | 13.79 | 27.06 | 54.42 | 95.75 | 119.83 | 26.5 |
| 6.2 | 14.18 | 28.53 | 57.50 | 100.66 | 126.98 | 27.2 |
| 6.4 | 14.58 | 30.04 | 60.68 | 105.69 | 134.34 | 28.0 |
| 6.6 | 14.97 | 31.58 | 63.94 | 110.85 | 141.91 | 28.7 |
| 6.8 | 15.37 | 33.16 | 67.28 | 116.13 | 149.68 | 29.4 |
| 6.9 | 15.76 | 34.78 | 70.71 | 121.53 | 157.66 | 30.0 |

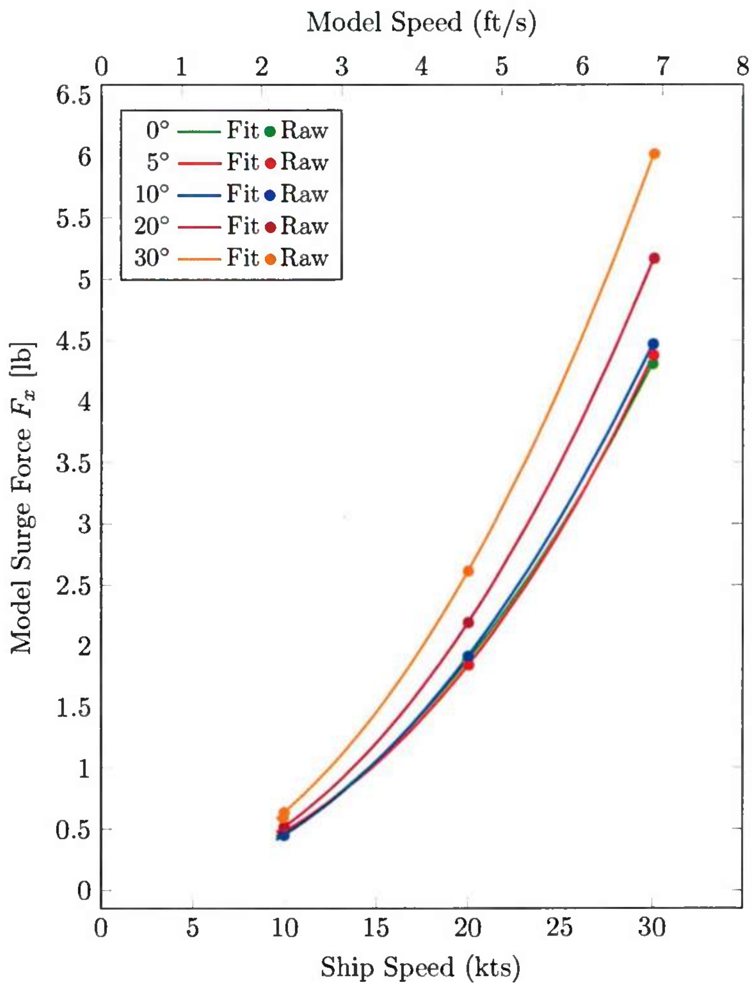



**Figure E-14: Surge force, varied rudder angle, single unit, rigid mount**

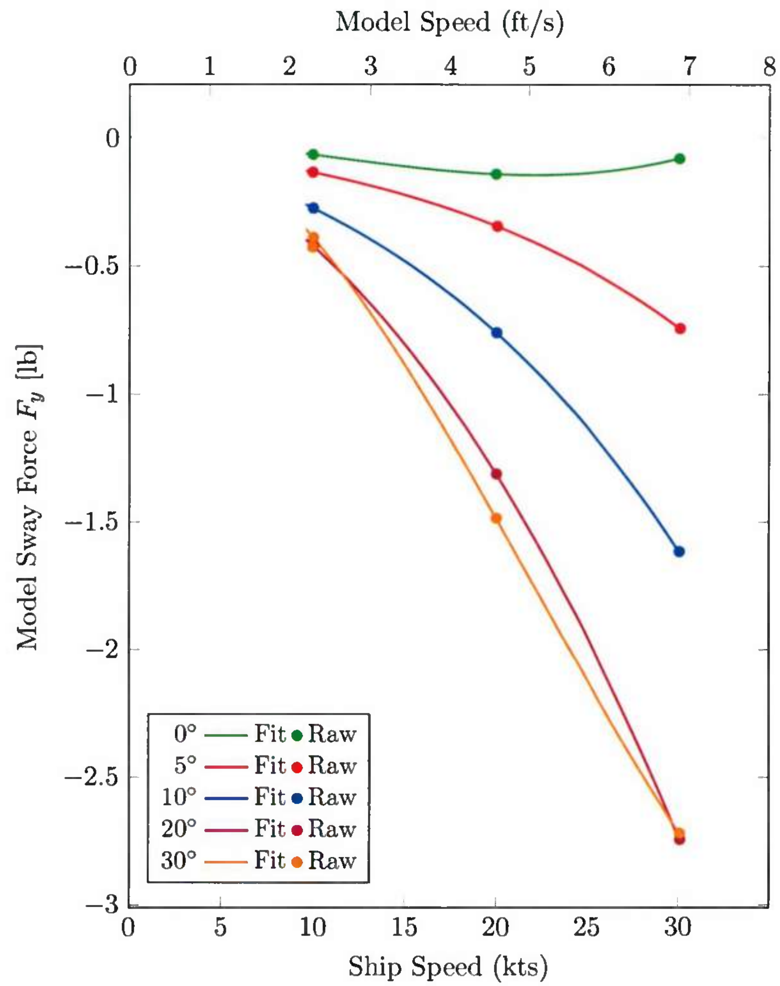



**Figure E-15: Sway force, varied rudder angle, single unit, rigid mount**

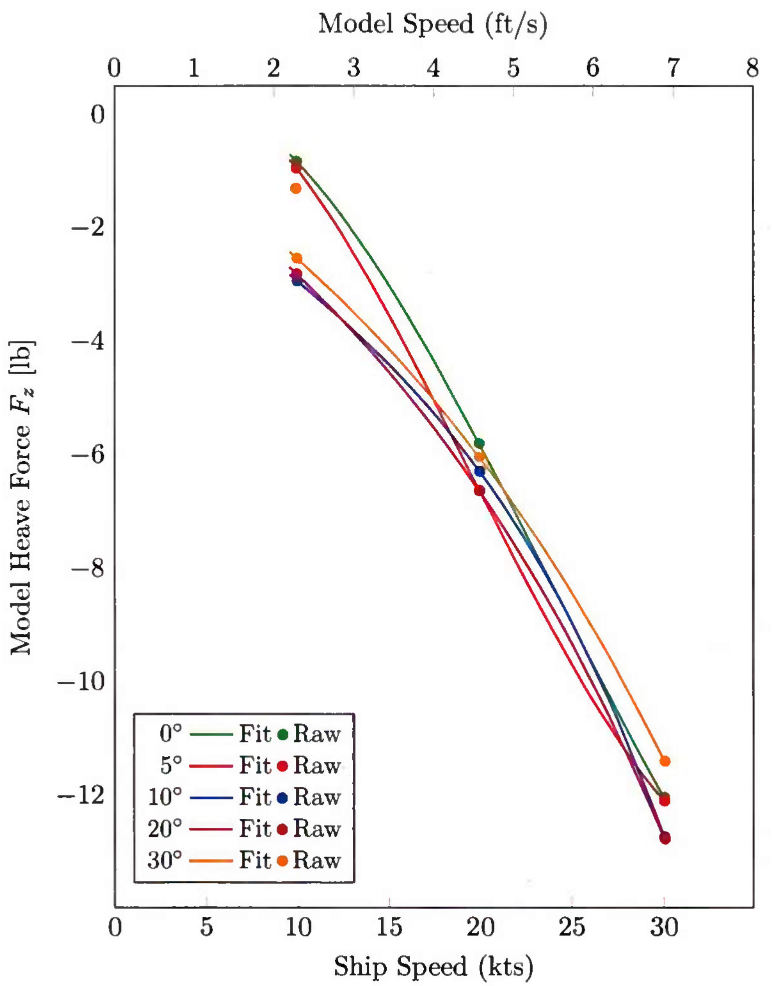



Figure E-16: Heave force, varied rudder angle, single unit, rigid mount

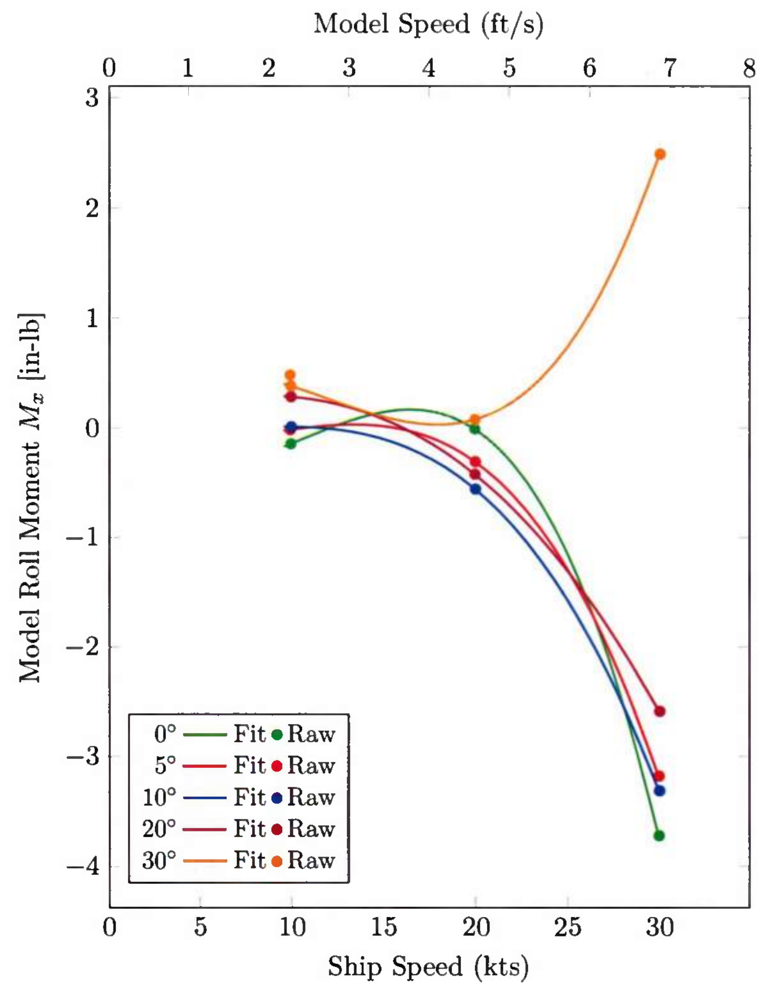



Figure E-17: Roll moment, varied rudder angle, single unit, rigid mount

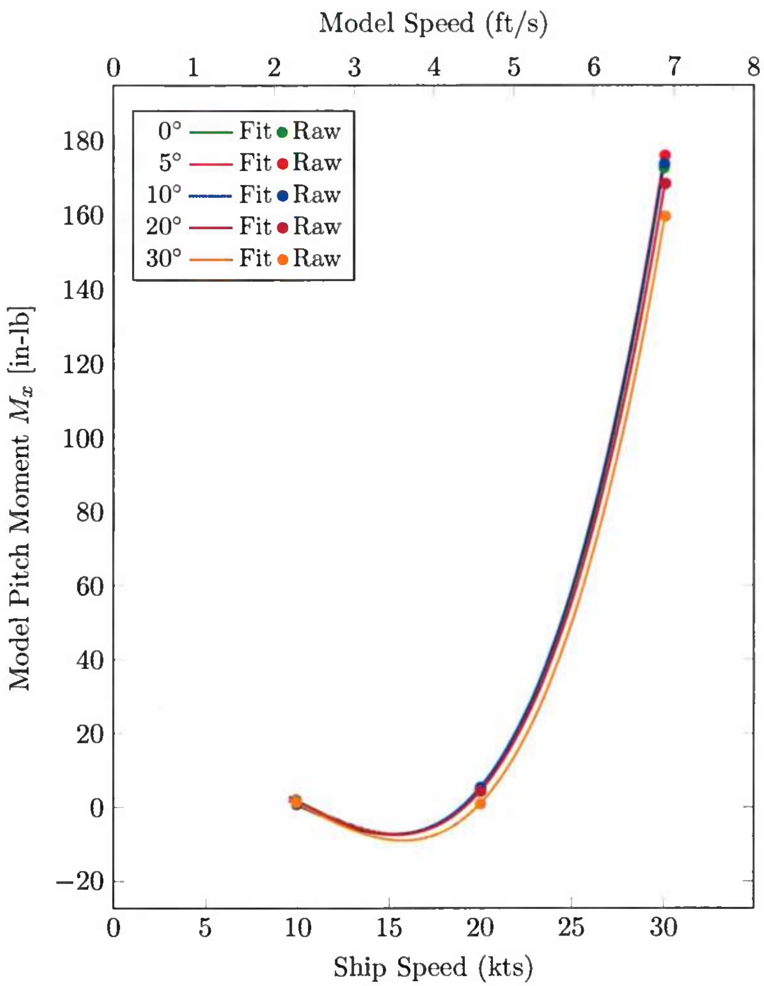



**Figure E-18: Pitch moment, varied rudder angle, single unit, rigid mount**

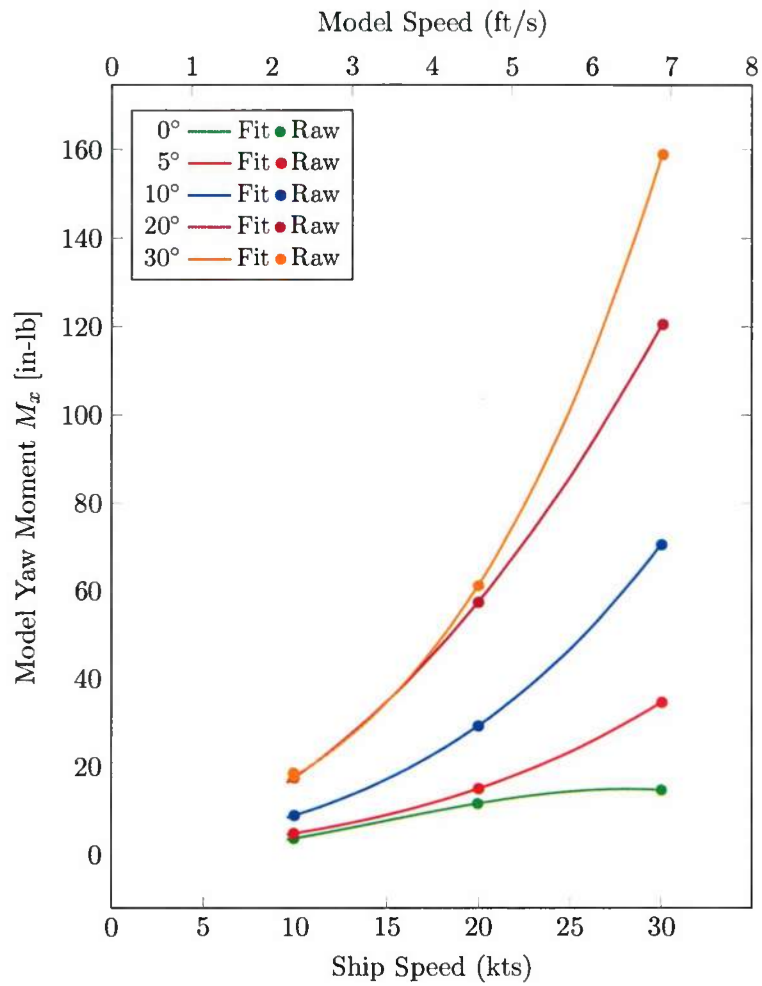



**Figure E-19: Yaw moment, varied rudder angle, single unit, rigid mount**

## Three Unit Seatrain, Varied Yaw on First Unit, Rigid Mount, Tests 17, 18 and 19

**Table E-15: First unit of three unit seatrain, varied yaw on first unit, rigid mount**

| | First Unit 0° Yaw Angle, Second Unit 0° Yaw Angle, Third Unit 0° Yaw Angle | | | | | | First Unit 5° Yaw Angle, Second Unit 0° Yaw Angle, Third Unit 0° Yaw Angle | | | | | | First Unit 10° Yaw Angle, Second Unit 0° Yaw Angle, Third Unit 0° Yaw Angle | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $V_{model}$ [ft/s] | $F_x$ [lbs] | $F_y$ [lbs] | $F_z$ [lbs] | $M_x$ [in-lbs] | $M_y$ [in-lbs] | $M_z$ [in-lbs] | $F_x$ [lbs] | $F_y$ [lbs] | $F_z$ [lbs] | $M_x$ [in-lbs] | $M_y$ [in-lbs] | $M_z$ [in-lbs] | $F_x$ [lbs] | $F_y$ [lbs] | $F_z$ [lbs] | $M_x$ [in-lbs] | $M_y$ [in-lbs] | $M_z$ [in-lbs] | $V_{ship}$ [kts] |
| 2.3 | 0.46 | 0.08 | −2.63 | 0.05 | 24.72 | −0.69 | 0.39 | 0.38 | −1.30 | 0.66 | −2.69 | −15.06 | 0.61 | 1.11 | −3.94 | −5.61 | −7.37 | 50.05 | 10 |
| 2.5 | 0.55 | 0.09 | −2.87 | 0.11 | 19.79 | −0.61 | 0.52 | 0.55 | −1.91 | 0.77 | −3.61 | −21.11 | 0.74 | 1.32 | −4.46 | −6.63 | −8.37 | 60.85 | 11 |
| 2.8 | 0.64 | 0.09 | −3.12 | 0.17 | 14.50 | −0.53 | 0.67 | 0.74 | −2.55 | 0.88 | −4.57 | −27.48 | 0.88 | 1.55 | −5.01 | −7.73 | −9.53 | 72.76 | 12 |
| 3.0 | 0.74 | 0.09 | −3.39 | 0.23 | 9.09 | −0.46 | 0.82 | 0.93 | −3.19 | 0.99 | −5.57 | −34.06 | 1.04 | 1.81 | −5.61 | −8.89 | −10.91 | 85.80 | 13 |
| 3.2 | 0.84 | 0.10 | −3.68 | 0.29 | 3.79 | −0.40 | 0.97 | 1.12 | −3.83 | 1.10 | −6.58 | −40.71 | 1.22 | 2.10 | −6.27 | −10.11 | −12.51 | 99.99 | 14 |
| 3.4 | 0.96 | 0.10 | −3.98 | 0.35 | −1.14 | −0.37 | 1.12 | 1.31 | −4.45 | 1.20 | −7.60 | −47.32 | 1.42 | 2.44 | −6.98 | −11.40 | −14.39 | 115.34 | 15 |
| 3.7 | 1.08 | 0.11 | −4.31 | 0.40 | −5.46 | −0.37 | 1.27 | 1.49 | −5.02 | 1.29 | −8.59 | −53.75 | 1.63 | 2.81 | −7.75 | −12.74 | −16.56 | 131.86 | 16 |
| 3.9 | 1.21 | 0.11 | −4.67 | 0.44 | −8.92 | −0.41 | 1.42 | 1.67 | −5.54 | 1.37 | −9.56 | −59.87 | 1.86 | 3.22 | −8.58 | −14.13 | −19.07 | 149.58 | 17 |
| 4.1 | 1.34 | 0.12 | −5.06 | 0.48 | −11.28 | −0.49 | 1.55 | 1.84 | −5.99 | 1.43 | −10.47 | −65.57 | 2.12 | 3.68 | −9.49 | −15.58 | −21.93 | 168.50 | 18 |
| 4.4 | 1.49 | 0.13 | −5.48 | 0.50 | −12.31 | −0.63 | 1.68 | 1.99 | −6.36 | 1.48 | −11.32 | −70.71 | 2.39 | 4.18 | −10.47 | −17.07 | −25.19 | 188.65 | 19 |
| 4.6 | 1.64 | 0.13 | −5.95 | 0.51 | −11.74 | −0.82 | 1.79 | 2.11 | −6.62 | 1.51 | −12.08 | −75.17 | 2.69 | 4.74 | −11.53 | −18.60 | −28.87 | 210.04 | 20 |
| 4.8 | 1.81 | 0.14 | −6.45 | 0.50 | −9.34 | −1.09 | 1.88 | 2.22 | −6.76 | 1.52 | −12.75 | −78.83 | | | | | | | 21 |
| 5.0 | 1.98 | 0.15 | −7.00 | 0.47 | −4.87 | −1.43 | 1.96 | 2.30 | −6.77 | 1.51 | −13.29 | −81.55 | | | | | | | 22 |
| 5.3 | 2.16 | 0.16 | −7.60 | 0.43 | 1.93 | −1.85 | 2.01 | 2.35 | −6.64 | 1.47 | −13.70 | −83.21 | | | | | | | 23 |
| 5.5 | 2.35 | 0.17 | −8.25 | 0.36 | 11.29 | −2.36 | 2.04 | 2.36 | −6.33 | 1.41 | −13.95 | −83.68 | | | | | | | 24 |
| 5.7 | 2.55 | 0.18 | −8.96 | 0.27 | 23.47 | −2.97 | | | | | | | | | | | | | 25 |
| 6.0 | 2.76 | 0.19 | −9.72 | 0.15 | 38.70 | −3.68 | | | | | | | | | | | | | 26 |
| 6.2 | 2.98 | 0.20 | −10.55 | 0.01 | 57.23 | −4.51 | | | | | | | | | | | | | 27 |
| 6.4 | 3.21 | 0.21 | −11.45 | −0.16 | 79.30 | −5.45 | | | | | | | | | | | | | 28 |
| 6.7 | 3.44 | 0.23 | −12.41 | −0.37 | 105.16 | −6.52 | | | | | | | | | | | | | 29 |
| 6.9 | 3.69 | 0.25 | −13.45 | −0.61 | 135.05 | −7.73 | | | | | | | | | | | | | 30 |

**Table E-16: Second unit of three unit seatrain, varied yaw on first unit, rigid mount**

| | First Unit 0° Yaw Angle<br>Second Unit 0° Yaw Angle<br>Third Unit 0° Yaw Angle | | | | | | First Unit 5° Yaw Angle<br>Second Unit 0° Yaw Angle<br>Third Unit 0° Yaw Angle | | | | | | First Unit 10° Yaw Angle<br>Second Unit 0° Yaw Angle<br>Third Unit 0° Yaw Angle | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $V_{model}$ [ft/s] | $F_x$ [lbs] | $F_y$ [lbs] | $F_z$ [lbs] | $M_x$ [in-lbs] | $M_y$ [in-lbs] | $M_z$ [in-lbs] | $F_x$ [lbs] | $F_y$ [lbs] | $F_z$ [lbs] | $M_x$ [in-lbs] | $M_y$ [in-lbs] | $M_z$ [in-lbs] | $F_x$ [lbs] | $F_y$ [lbs] | $F_z$ [lbs] | $M_x$ [in-lbs] | $M_y$ [in-lbs] | $M_z$ [in-lbs] | $V_{ship}$ [kts] |
| 2.3 | 0.55 | 0.07 | −5.74 | 0.67 | 49.44 | 0.13 | 0.34 | −0.21 | −0.84 | −0.53 | 3.14 | 6.64 | 0.49 | −0.59 | −2.32 | −1.07 | 2.57 | 17.89 | 10 |
| 2.5 | 0.63 | 0.06 | −5.39 | 0.62 | 42.70 | 0.14 | 0.48 | −0.30 | −1.31 | −0.57 | 3.87 | 9.44 | 0.58 | −0.70 | −2.70 | −1.20 | 3.62 | 20.90 | 11 |
| 2.8 | 0.71 | 0.06 | −5.00 | 0.56 | 35.40 | 0.14 | 0.62 | −0.40 | −1.80 | −0.61 | 4.63 | 12.41 | 0.68 | −0.83 | −3.08 | −1.40 | 4.69 | 24.63 | 12 |
| 3.0 | 0.80 | 0.05 | −4.61 | 0.51 | 27.91 | 0.13 | 0.77 | −0.50 | −2.29 | −0.65 | 5.39 | 15.50 | 0.79 | −0.99 | −3.47 | −1.67 | 5.73 | 29.20 | 13 |
| 3.2 | 0.90 | 0.05 | −4.24 | 0.46 | 20.63 | 0.11 | 0.92 | −0.60 | −2.78 | −0.69 | 6.16 | 18.65 | 0.91 | −1.18 | −3.86 | −2.03 | 6.74 | 34.75 | 14 |
| 3.4 | 1.01 | 0.05 | −3.93 | 0.42 | 13.94 | 0.09 | 1.07 | −0.70 | −3.24 | −0.73 | 6.91 | 21.81 | 1.05 | −1.41 | −4.25 | −2.49 | 7.66 | 41.38 | 15 |
| 3.7 | 1.13 | 0.05 | −3.71 | 0.39 | 8.25 | 0.06 | 1.21 | −0.81 | −3.66 | −0.77 | 7.64 | 24.92 | 1.20 | −1.67 | −4.63 | −3.07 | 8.47 | 49.23 | 16 |
| 3.9 | 1.27 | 0.05 | −3.61 | 0.38 | 3.92 | 0.02 | 1.35 | −0.91 | −4.04 | −0.81 | 8.32 | 27.93 | 1.36 | −1.98 | −5.00 | −3.77 | 9.14 | 58.43 | 17 |
| 4.1 | 1.42 | 0.05 | −3.68 | 0.40 | 1.36 | −0.03 | 1.48 | −1.00 | −4.35 | −0.85 | 8.96 | 30.77 | 1.54 | −2.33 | −5.36 | −4.63 | 9.63 | 69.09 | 18 |
| 4.4 | 1.59 | 0.05 | −3.93 | 0.44 | 0.96 | −0.10 | 1.59 | −1.09 | −4.58 | −0.89 | 9.53 | 33.40 | 1.73 | −2.74 | −5.69 | −5.64 | 9.92 | 81.34 | 19 |
| 4.6 | 1.77 | 0.06 | −4.40 | 0.51 | 3.09 | −0.18 | 1.70 | −1.18 | −4.73 | −0.94 | 10.02 | 35.76 | 1.93 | −3.19 | −6.01 | −6.83 | 9.96 | 95.31 | 20 |
| 4.8 | 1.97 | 0.07 | −5.13 | 0.62 | 8.16 | −0.27 | 1.78 | −1.25 | −4.78 | −0.99 | 10.42 | 37.80 | | | | | | | 21 |
| 5.0 | 2.19 | 0.08 | −6.14 | 0.76 | 16.55 | −0.37 | 1.84 | −1.31 | −4.71 | −1.04 | 10.72 | 39.46 | | | | | | | 22 |
| 5.3 | 2.43 | 0.10 | −7.48 | 0.96 | 28.65 | −0.49 | 1.88 | −1.36 | −4.51 | −1.09 | 10.90 | 40.68 | | | | | | | 23 |
| 5.5 | 2.70 | 0.12 | −9.16 | 1.20 | 44.85 | −0.63 | 1.90 | −1.40 | −4.16 | −1.15 | 10.95 | 41.40 | | | | | | | 24 |
| 5.7 | 2.98 | 0.14 | −11.23 | 1.49 | 65.53 | −0.79 | | | | | | | | | | | | | 25 |
| 6.0 | 3.29 | 0.17 | −13.72 | 1.84 | 91.10 | −0.96 | | | | | | | | | | | | | 26 |
| 6.2 | 3.62 | 0.21 | −16.66 | 2.25 | 121.93 | −1.15 | | | | | | | | | | | | | 27 |
| 6.4 | 3.98 | 0.25 | −20.07 | 2.73 | 158.42 | −1.36 | | | | | | | | | | | | | 28 |
| 6.7 | 4.36 | 0.30 | −24.01 | 3.28 | 200.95 | −1.60 | | | | | | | | | | | | | 29 |
| 6.9 | 4.77 | 0.35 | −28.49 | 3.91 | 249.91 | −1.85 | | | | | | | | | | | | | 30 |

Table E-17: Third unit of three unit seatrain, varied yaw on first unit, rigid mount

| $V_{model}$ | First Unit 0° Yaw Angle, Second Unit 0° Yaw Angle, Third Unit 0° Yaw Angle | | | | | | First Unit 5° Yaw Angle, Second Unit 0° Yaw Angle, Third Unit 0° Yaw Angle | | | | | | First Unit 10° Yaw Angle, Second Unit 0° Yaw Angle, Third Unit 0° Yaw Angle | | | | | | $V_{ship}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $F_x$ | $F_y$ | $F_z$ | $M_x$ | $M_y$ | $M_z$ | $F_x$ | $F_y$ | $F_z$ | $M_x$ | $M_y$ | $M_z$ | $F_x$ | $F_y$ | $F_z$ | $M_x$ | $M_y$ | $M_z$ | |
| [ft/s] | [lbs] | [lbs] | [lbs] | [in-lbs] | [in-lbs] | [in-lbs] | [lbs] | [lbs] | [lbs] | [in-lbs] | [in-lbs] | [in-lbs] | [lbs] | [lbs] | [lbs] | [in-lbs] | [in-lbs] | [in-lbs] | [kts] |
| 2.3 | 0.51 | −0.05 | −1.85 | 0.04 | 41.45 | −3.12 | 0.36 | −0.03 | −0.51 | 0.15 | 3.46 | 1.93 | 0.45 | 0.09 | −2.26 | −0.16 | 5.92 | −1.52 | 10 |
| 2.5 | 0.59 | −0.04 | −1.99 | 0.07 | 36.43 | −2.57 | 0.49 | −0.05 | −0.91 | 0.08 | 5.11 | 2.46 | 0.54 | 0.09 | −2.73 | −0.20 | 7.97 | −1.88 | 11 |
| 2.8 | 0.69 | −0.03 | −2.14 | 0.09 | 31.00 | −1.96 | 0.63 | −0.06 | −1.31 | 0.00 | 6.86 | 3.02 | 0.64 | 0.10 | −3.21 | −0.22 | 10.10 | −2.26 | 12 |
| 3.0 | 0.80 | −0.02 | −2.30 | 0.11 | 25.49 | −1.31 | 0.77 | −0.07 | −1.72 | −0.08 | 8.67 | 3.60 | 0.75 | 0.10 | −3.69 | −0.24 | 12.29 | −2.68 | 13 |
| 3.2 | 0.91 | −0.01 | −2.46 | 0.11 | 20.20 | −0.64 | 0.91 | −0.08 | −2.13 | −0.16 | 10.51 | 4.19 | 0.87 | 0.12 | −4.16 | −0.26 | 14.48 | −3.13 | 14 |
| 3.4 | 1.04 | 0.00 | −2.64 | 0.10 | 15.46 | 0.01 | 1.06 | −0.09 | −2.50 | −0.25 | 12.34 | 4.79 | 1.00 | 0.14 | −4.62 | −0.26 | 16.64 | −3.61 | 15 |
| 3.7 | 1.17 | 0.01 | −2.83 | 0.08 | 11.58 | 0.63 | 1.20 | −0.11 | −2.85 | −0.33 | 14.13 | 5.38 | 1.15 | 0.17 | −5.05 | −0.26 | 18.72 | −4.11 | 16 |
| 3.9 | 1.32 | 0.02 | −3.04 | 0.05 | 8.88 | 1.19 | 1.34 | −0.12 | −3.14 | −0.40 | 15.85 | 5.96 | 1.31 | 0.21 | −5.44 | −0.24 | 20.68 | −4.65 | 17 |
| 4.1 | 1.48 | 0.03 | −3.28 | −0.01 | 7.67 | 1.67 | 1.46 | −0.13 | −3.38 | −0.47 | 17.45 | 6.52 | 1.49 | 0.26 | −5.79 | −0.21 | 22.47 | −5.22 | 18 |
| 4.4 | 1.65 | 0.04 | −3.53 | −0.08 | 8.28 | 2.04 | 1.58 | −0.13 | −3.55 | −0.53 | 18.90 | 7.05 | 1.68 | 0.33 | −6.09 | −0.17 | 24.06 | −5.81 | 19 |
| 4.6 | 1.83 | 0.05 | −3.82 | −0.18 | 11.02 | 2.28 | 1.68 | −0.14 | −3.63 | −0.58 | 20.17 | 7.55 | 1.89 | 0.41 | −6.32 | −0.11 | 25.40 | −6.43 | 20 |
| 4.8 | 2.03 | 0.05 | −4.13 | −0.31 | 16.19 | 2.36 | 1.77 | −0.15 | −3.62 | −0.61 | 21.22 | 8.00 | | | | | | | 21 |
| 5.0 | 2.24 | 0.05 | −4.48 | −0.46 | 24.13 | 2.26 | 1.84 | −0.15 | −3.51 | −0.63 | 22.02 | 8.39 | | | | | | | 22 |
| 5.3 | 2.46 | 0.05 | −4.86 | −0.64 | 35.15 | 1.96 | 1.89 | −0.15 | −3.27 | −0.63 | 22.53 | 8.72 | | | | | | | 23 |
| 5.5 | 2.70 | 0.05 | −5.28 | −0.85 | 49.56 | 1.44 | 1.92 | −0.14 | −2.90 | −0.61 | 22.72 | 8.98 | | | | | | | 24 |
| 5.7 | 2.95 | 0.04 | −5.75 | −1.09 | 67.69 | 0.66 | | | | | | | | | | | | | 25 |
| 6.0 | 3.22 | 0.04 | −6.26 | −1.38 | 89.84 | −0.40 | | | | | | | | | | | | | 26 |
| 6.2 | 3.50 | 0.02 | −6.81 | −1.70 | 116.33 | −1.75 | | | | | | | | | | | | | 27 |
| 6.4 | 3.80 | 0.00 | −7.42 | −2.06 | 147.48 | −3.43 | | | | | | | | | | | | | 28 |
| 6.7 | 4.12 | −0.02 | −8.07 | −2.46 | 183.61 | −5.46 | | | | | | | | | | | | | 29 |
| 6.9 | 4.45 | −0.04 | −8.79 | −2.91 | 225.04 | −7.86 | | | | | | | | | | | | | 30 |

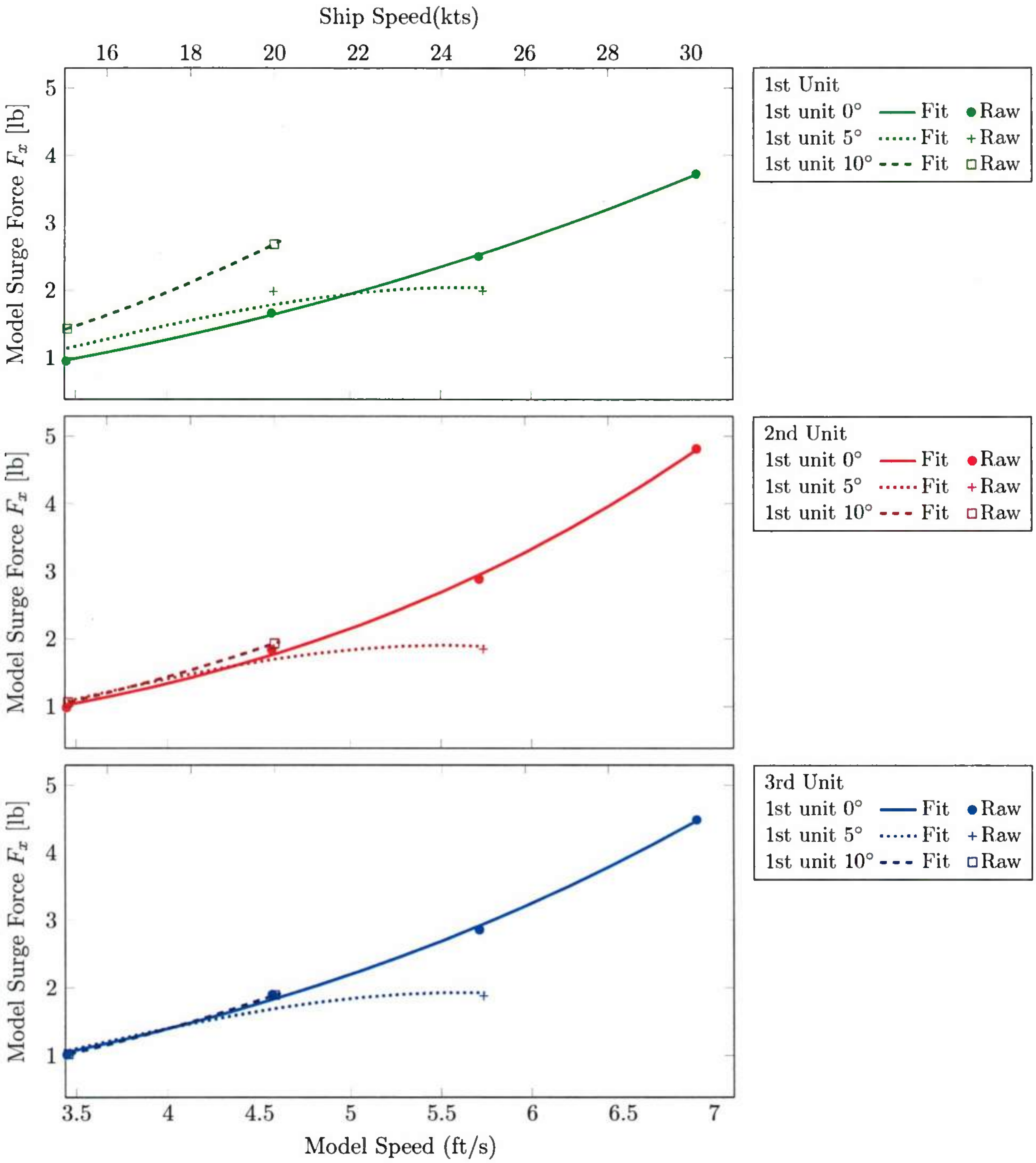



**Figure E-20: Surge force, three unit seatrain, varied yaw on first unit, rigid mount**

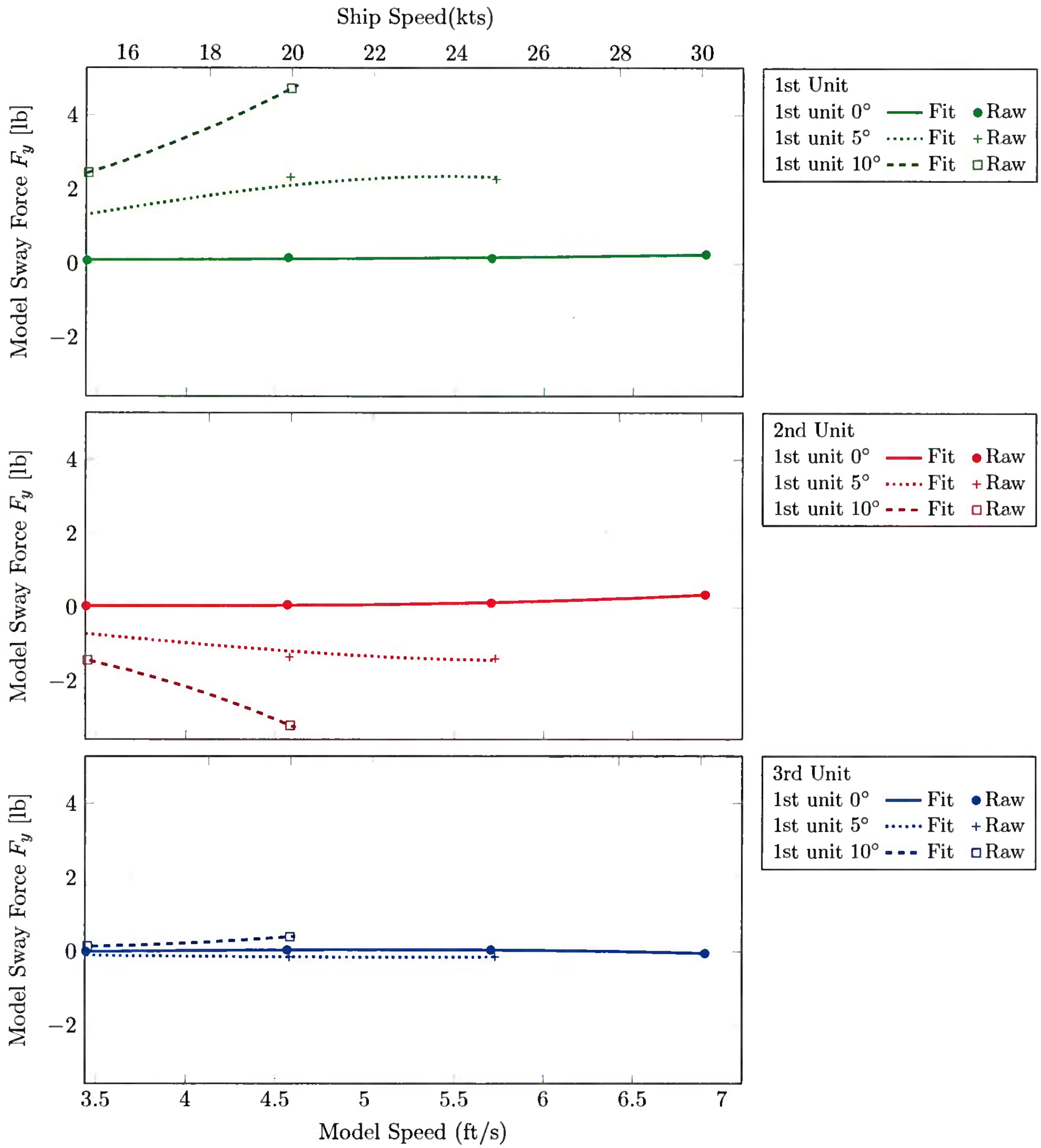



**Figure E-21: Sway force, three unit seatrain, varied yaw on first unit, rigid mount**

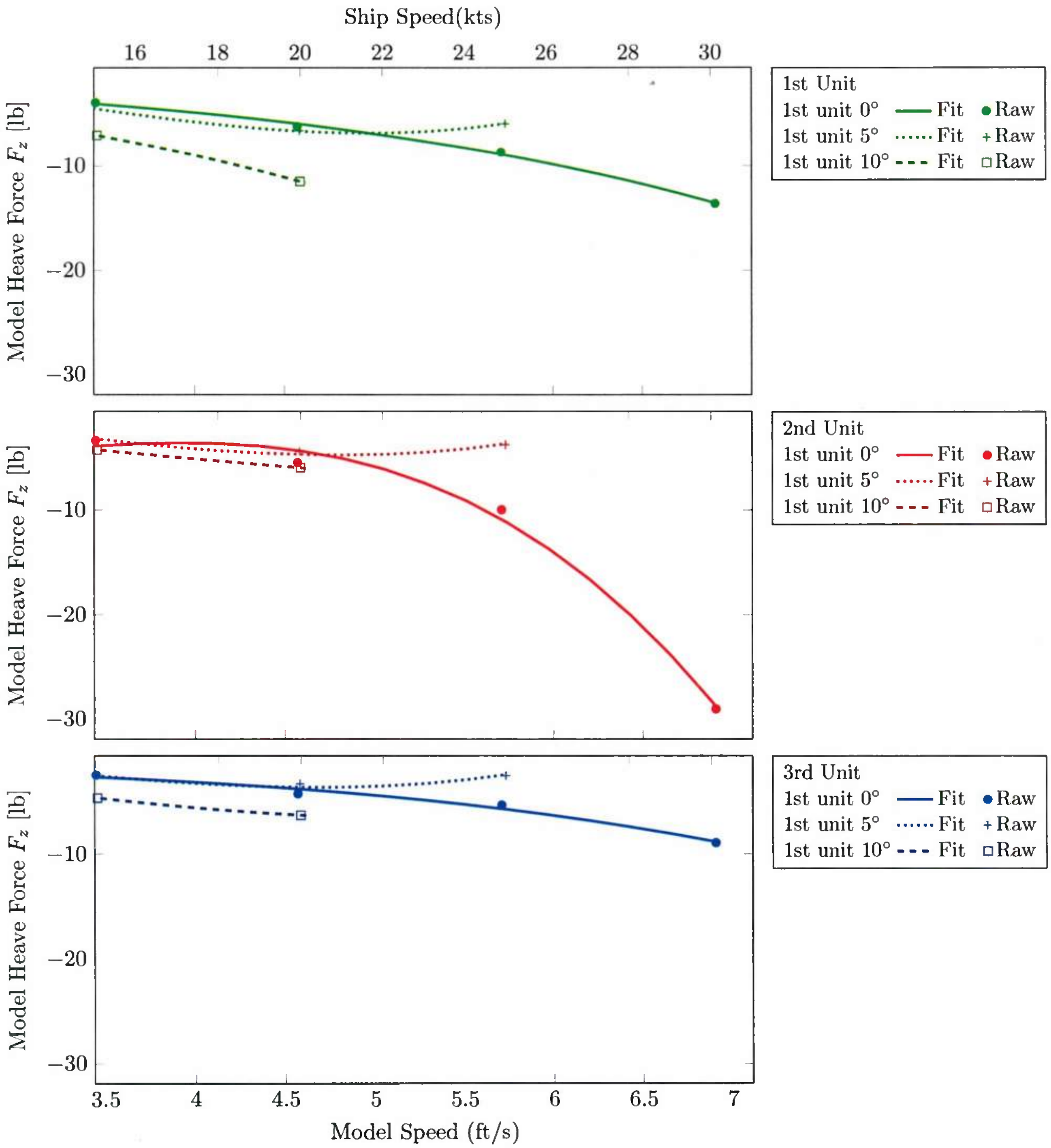



**Figure E-22: Heave force, three unit seatrain, varied yaw on first unit, rigid mount**

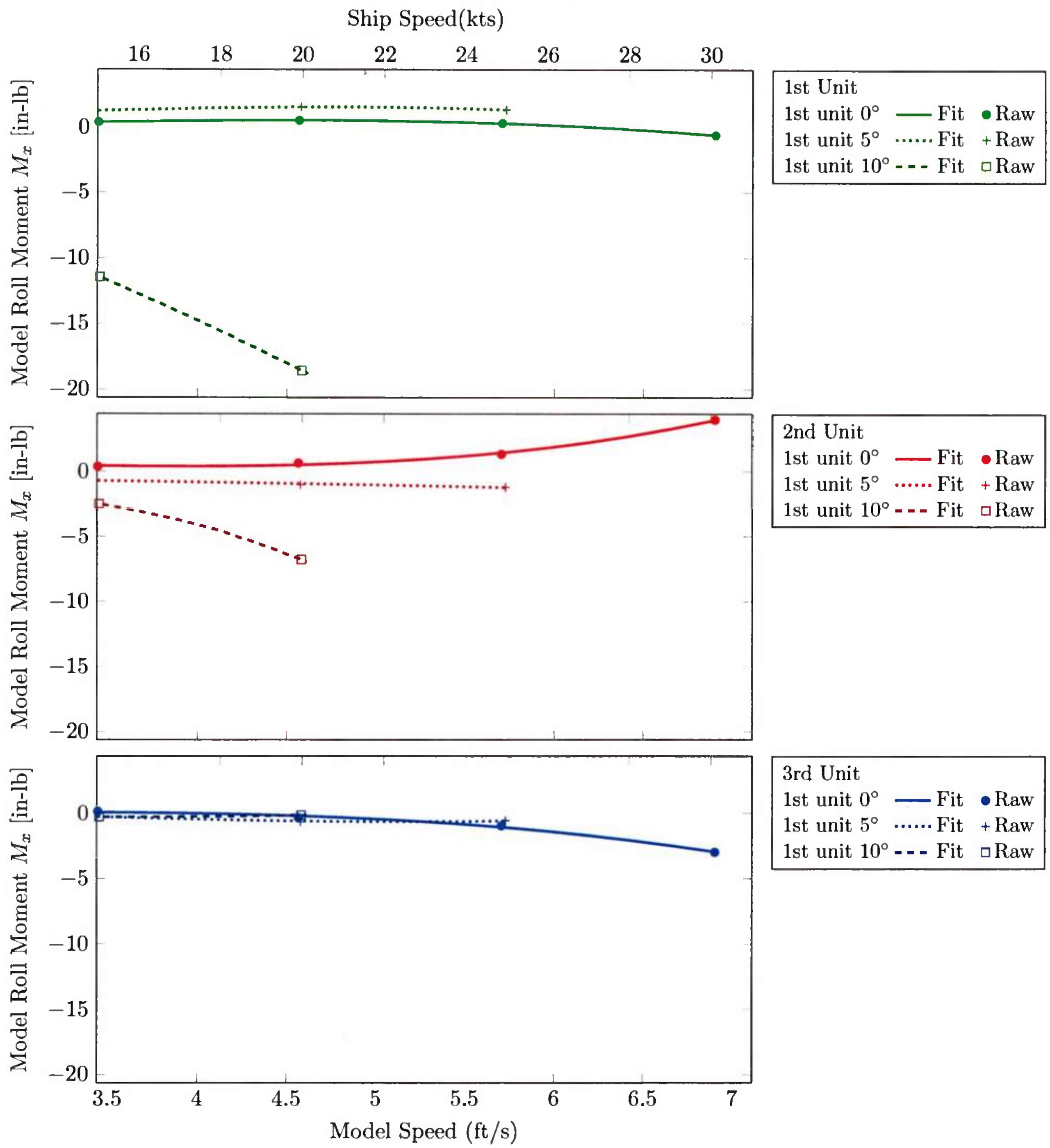



**Figure E-23: Roll moment, three unit seatrain, varied yaw on first unit, rigid mount**

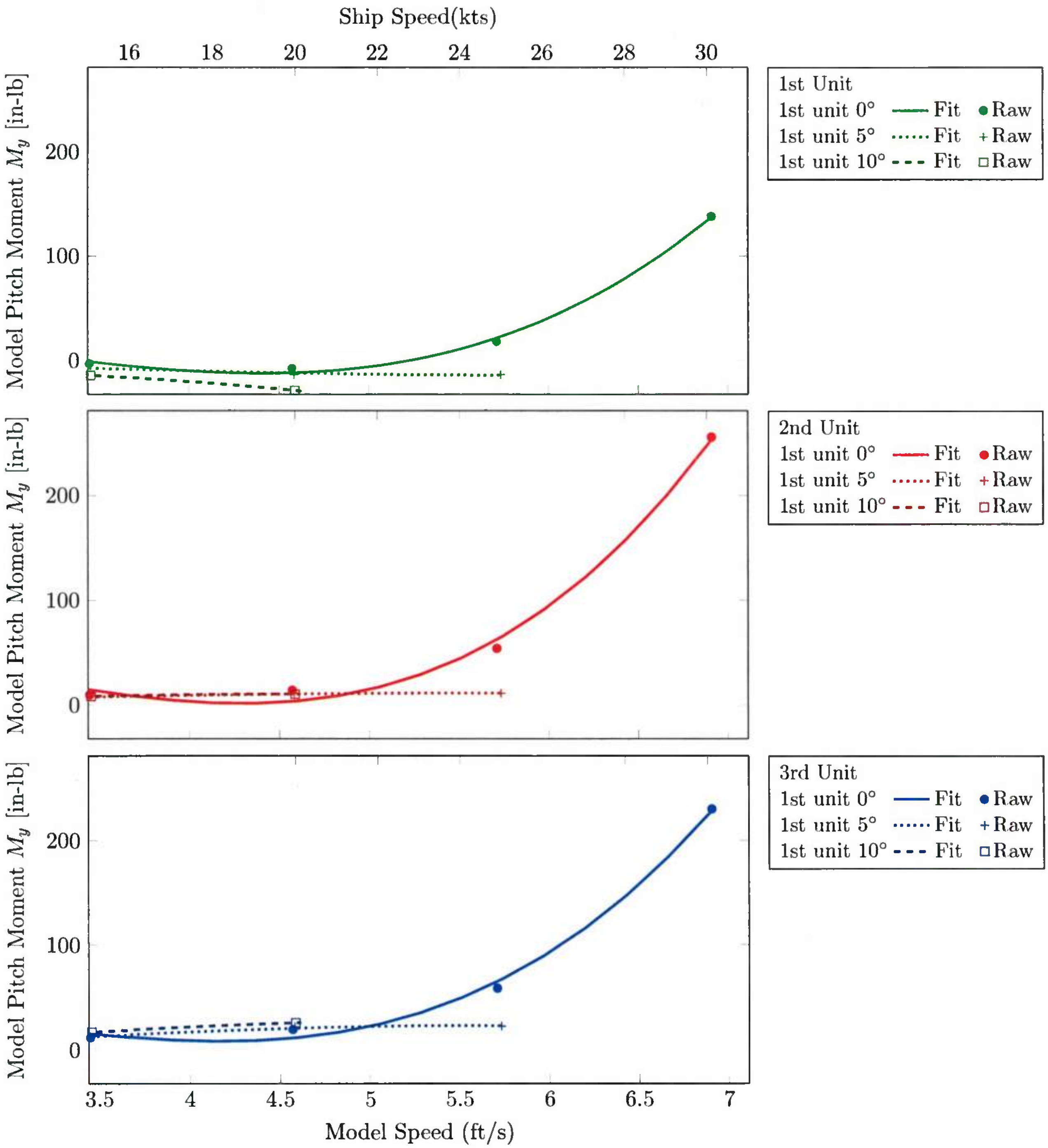



**Figure E-24: Pitch moment, three unit seatrain, varied yaw on first unit, rigid mount**

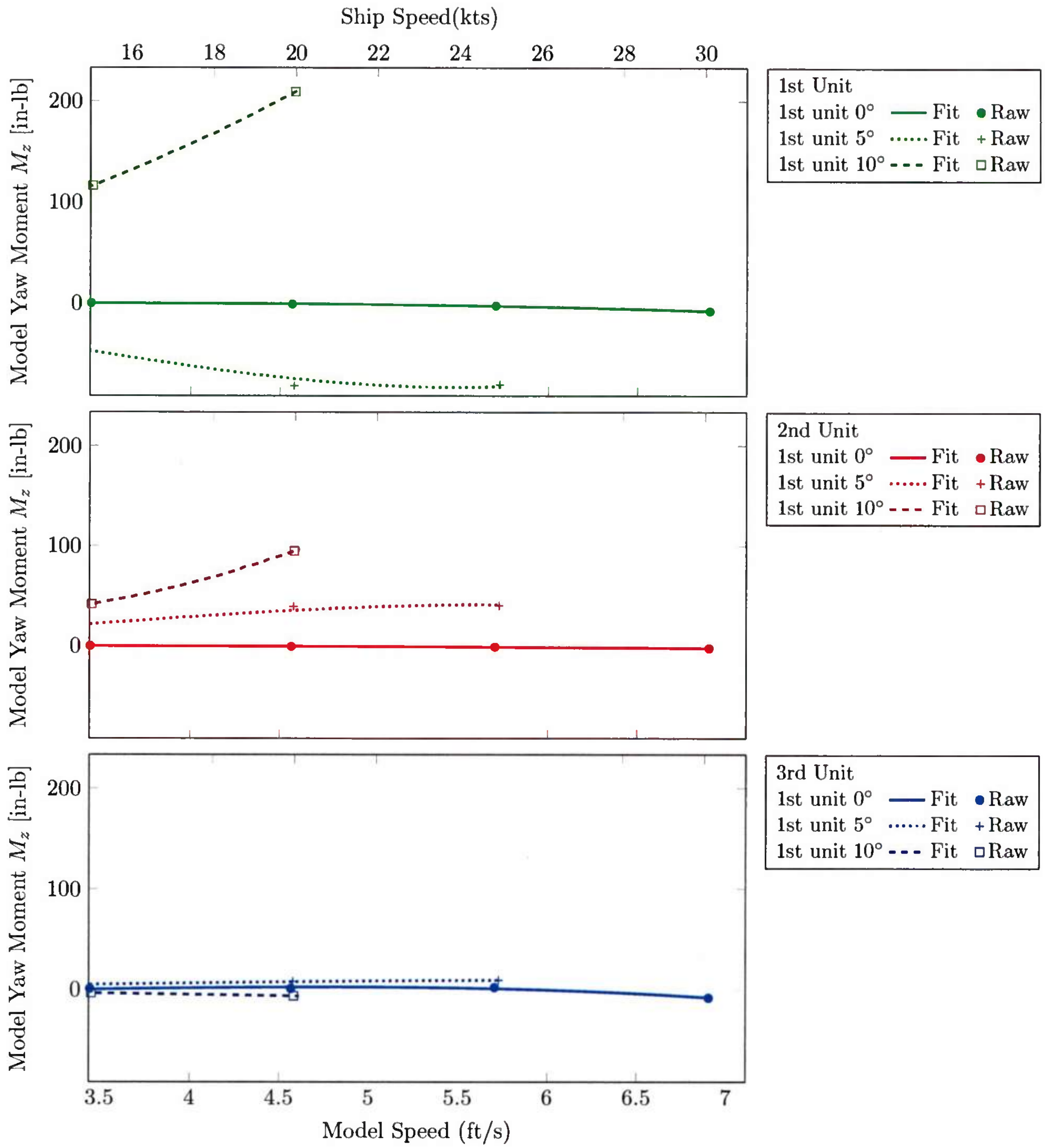



**Figure E-25: Yaw moment, three unit seatrain, varied yaw on first unit, rigid mount**

## Three Unit Seatrain, Varied Yaw on First Unit, Rigid Mount, Tests 17, 18 and 19

### Table E-18: First unit of three unit seatrain, varied yaw on third unit, rigid mount

| | First Unit 0° Yaw Angle, Second Unit 0° Yaw Angle, Third Unit 0° Yaw Angle | | | | | | First Unit 0° Yaw Angle, Second Unit 0° Yaw Angle, Third Unit 5° Yaw Angle | | | | | | First Unit 0° Yaw Angle, Second Unit 0° Yaw Angle, Third Unit 10° Yaw Angle | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $V_{model}$ [ft/s] | $F_x$ [lbs] | $F_y$ [lbs] | $F_z$ [lbs] | $M_x$ [in-lbs] | $M_y$ [in-lbs] | $M_z$ [in-lbs] | $F_x$ [lbs] | $F_y$ [lbs] | $F_z$ [lbs] | $M_x$ [in-lbs] | $M_y$ [in-lbs] | $M_z$ [in-lbs] | $F_x$ [lbs] | $F_y$ [lbs] | $F_z$ [lbs] | $M_x$ [in-lbs] | $M_y$ [in-lbs] | $M_z$ [in-lbs] | $V_{ship}$ [kts] |
| 2.3 | 0.46 | 0.08 | −2.63 | 0.05 | 24.72 | −0.69 | 0.46 | 0.01 | −2.63 | −0.08 | 26.13 | 3.53 | 0.36 | 0.09 | −3.29 | 0.16 | 0.90 | 0.02 | 10 |
| 2.5 | 0.55 | 0.09 | −2.87 | 0.11 | 19.79 | −0.61 | 0.54 | 0.02 | −2.85 | −0.02 | 21.18 | 3.23 | 0.45 | 0.09 | −3.36 | 0.19 | −0.71 | 0.05 | 11 |
| 2.8 | 0.64 | 0.09 | −3.12 | 0.17 | 14.50 | −0.53 | 0.63 | 0.03 | −3.07 | 0.04 | 15.86 | 2.86 | 0.56 | 0.09 | −3.44 | 0.21 | −2.29 | 0.10 | 12 |
| 3.0 | 0.74 | 0.09 | −3.39 | 0.23 | 9.09 | −0.46 | 0.73 | 0.04 | −3.30 | 0.10 | 10.40 | 2.44 | 0.67 | 0.09 | −3.52 | 0.23 | −3.75 | 0.17 | 13 |
| 3.2 | 0.84 | 0.10 | −3.68 | 0.29 | 3.79 | −0.40 | 0.83 | 0.05 | −3.55 | 0.16 | 5.05 | 1.98 | 0.79 | 0.09 | −3.63 | 0.25 | −5.01 | 0.27 | 14 |
| 3.4 | 0.96 | 0.10 | −3.98 | 0.35 | −1.14 | −0.37 | 0.94 | 0.06 | −3.81 | 0.21 | 0.05 | 1.48 | 0.92 | 0.09 | −3.76 | 0.27 | −5.96 | 0.40 | 15 |
| 3.7 | 1.08 | 0.11 | −4.31 | 0.40 | −5.46 | −0.37 | 1.07 | 0.07 | −4.10 | 0.26 | −4.34 | 0.97 | 1.05 | 0.09 | −3.93 | 0.28 | −6.54 | 0.56 | 16 |
| 3.9 | 1.21 | 0.11 | −4.67 | 0.44 | −8.92 | −0.41 | 1.19 | 0.08 | −4.42 | 0.31 | −7.87 | 0.46 | 1.20 | 0.09 | −4.16 | 0.29 | −6.64 | 0.76 | 17 |
| 4.1 | 1.34 | 0.12 | −5.06 | 0.48 | −11.28 | −0.49 | 1.33 | 0.09 | −4.76 | 0.34 | −10.30 | −0.05 | 1.34 | 0.09 | −4.45 | 0.30 | −6.19 | 0.99 | 18 |
| 4.4 | 1.49 | 0.13 | −5.48 | 0.50 | −12.31 | −0.63 | 1.48 | 0.10 | −5.14 | 0.36 | −11.39 | −0.53 | 1.50 | 0.08 | −4.81 | 0.30 | −5.09 | 1.27 | 19 |
| 4.6 | 1.64 | 0.13 | −5.95 | 0.51 | −11.74 | −0.82 | 1.63 | 0.11 | −5.55 | 0.37 | −10.87 | −0.98 | 1.66 | 0.08 | −5.26 | 0.30 | −3.26 | 1.60 | 20 |
| 4.8 | 1.81 | 0.14 | −6.45 | 0.50 | −9.34 | −1.09 | 1.80 | 0.12 | −6.01 | 0.36 | −8.52 | −1.38 | 1.82 | 0.07 | −5.80 | 0.29 | −0.61 | 1.97 | 21 |
| 5.0 | 1.98 | 0.15 | −7.00 | 0.47 | −4.87 | −1.43 | 1.97 | 0.13 | −6.51 | 0.33 | −4.07 | −1.72 | 1.99 | 0.07 | −6.44 | 0.27 | 2.94 | 2.40 | 22 |
| 5.3 | 2.16 | 0.16 | −7.60 | 0.43 | 1.93 | −1.85 | 2.15 | 0.14 | −7.06 | 0.28 | 2.71 | −1.99 | 2.16 | 0.06 | −7.21 | 0.25 | 7.49 | 2.88 | 23 |
| 5.5 | 2.35 | 0.17 | −8.25 | 0.36 | 11.29 | −2.36 | 2.34 | 0.14 | −7.66 | 0.21 | 12.09 | −2.17 | 2.33 | 0.05 | −8.10 | 0.22 | 13.11 | 3.42 | 24 |
| 5.7 | 2.55 | 0.18 | −8.96 | 0.27 | 23.47 | −2.97 | 2.55 | 0.14 | −8.32 | 0.12 | 24.30 | −2.26 | | | | | | | 25 |
| 6.0 | 2.76 | 0.19 | −9.72 | 0.15 | 38.70 | −3.68 | 2.76 | 0.15 | −9.04 | 0.00 | 39.58 | −2.23 | | | | | | | 26 |
| 6.2 | 2.98 | 0.20 | −10.55 | 0.01 | 57.23 | −4.51 | 2.98 | 0.15 | −9.82 | −0.15 | 58.20 | −2.08 | | | | | | | 27 |
| 6.4 | 3.21 | 0.21 | −11.45 | −0.16 | 79.30 | −5.45 | 3.21 | 0.14 | −10.67 | −0.34 | 80.40 | −1.79 | | | | | | | 28 |
| 6.7 | 3.44 | 0.23 | −12.41 | −0.37 | 105.16 | −6.52 | 3.46 | 0.14 | −11.59 | −0.55 | 106.42 | −1.36 | | | | | | | 29 |
| 6.9 | 3.69 | 0.25 | −13.45 | −0.61 | 135.05 | −7.73 | | | | | | | | | | | | | 30 |

**Table E-19: Second unit of three unit seatrain, varied yaw on third unit, rigid mount**

| | First Unit 0° Yaw Angle Second Unit 0° Yaw Angle Third Unit 0° Yaw Angle | | | | | | First Unit 0° Yaw Angle Second Unit 0° Yaw Angle Third Unit 5° Yaw Angle | | | | | | First Unit 0° Yaw Angle Second Unit 0° Yaw Angle Third Unit 10° Yaw Angle | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $V_{model}$ | $F_x$ | $F_y$ | $F_z$ | $M_x$ | $M_y$ | $M_z$ | $F_x$ | $F_y$ | $F_z$ | $M_x$ | $M_y$ | $M_z$ | $F_x$ | $F_y$ | $F_z$ | $M_x$ | $M_y$ | $M_z$ | $V_{ship}$ |
| [ft/s] | [lbs] | [lbs] | [lbs] | [in-lbs] | [in-lbs] | [in-lbs] | [lbs] | [lbs] | [lbs] | [in-lbs] | [in-lbs] | [in-lbs] | [lbs] | [lbs] | [lbs] | [in-lbs] | [in-lbs] | [in-lbs] | [kts] |
| 2.3 | 0.55 | 0.07 | −5.74 | 0.67 | 49.44 | 0.13 | 0.59 | 0.04 | −6.29 | 0.37 | 55.53 | 0.50 | 0.49 | 0.06 | −3.37 | 0.50 | 5.50 | −3.37 | 10 |
| 2.5 | 0.63 | 0.06 | −5.39 | 0.62 | 42.70 | 0.14 | 0.65 | 0.05 | −5.89 | 0.38 | 48.26 | −0.12 | 0.58 | 0.06 | −3.34 | 0.51 | 5.14 | −3.76 | 11 |
| 2.8 | 0.71 | 0.06 | −5.00 | 0.56 | 35.40 | 0.14 | 0.72 | 0.06 | −5.44 | 0.39 | 40.33 | −0.81 | 0.67 | 0.06 | −3.31 | 0.51 | 4.95 | −4.17 | 12 |
| 3.0 | 0.80 | 0.05 | −4.61 | 0.51 | 27.91 | 0.13 | 0.80 | 0.07 | −4.97 | 0.41 | 32.16 | −1.59 | 0.77 | 0.07 | −3.29 | 0.52 | 5.02 | −4.62 | 13 |
| 3.2 | 0.90 | 0.05 | −4.24 | 0.46 | 20.63 | 0.11 | 0.89 | 0.08 | −4.52 | 0.43 | 24.17 | −2.43 | 0.88 | 0.07 | −3.31 | 0.53 | 5.43 | −5.11 | 14 |
| 3.4 | 1.01 | 0.05 | −3.93 | 0.42 | 13.94 | 0.09 | 0.99 | 0.10 | −4.13 | 0.46 | 16.79 | −3.33 | 1.00 | 0.08 | −3.38 | 0.54 | 6.27 | −5.64 | 15 |
| 3.7 | 1.13 | 0.05 | −3.71 | 0.39 | 8.25 | 0.06 | 1.10 | 0.11 | −3.82 | 0.49 | 10.43 | −4.29 | 1.13 | 0.08 | −3.52 | 0.57 | 7.62 | −6.22 | 16 |
| 3.9 | 1.27 | 0.05 | −3.61 | 0.38 | 3.92 | 0.02 | 1.23 | 0.13 | −3.64 | 0.53 | 5.51 | −5.28 | 1.28 | 0.09 | −3.74 | 0.60 | 9.57 | −6.85 | 17 |
| 4.1 | 1.42 | 0.05 | −3.68 | 0.40 | 1.36 | −0.03 | 1.37 | 0.15 | −3.62 | 0.58 | 2.45 | −6.31 | 1.43 | 0.10 | −4.07 | 0.65 | 12.20 | −7.54 | 18 |
| 4.4 | 1.59 | 0.05 | −3.93 | 0.44 | 0.96 | −0.10 | 1.53 | 0.17 | −3.79 | 0.64 | 1.68 | −7.36 | 1.59 | 0.12 | −4.51 | 0.70 | 15.60 | −8.29 | 19 |
| 4.6 | 1.77 | 0.06 | −4.40 | 0.51 | 3.09 | −0.18 | 1.71 | 0.19 | −4.18 | 0.71 | 3.61 | −8.43 | 1.76 | 0.13 | −5.09 | 0.78 | 19.85 | −9.10 | 20 |
| 4.8 | 1.97 | 0.07 | −5.13 | 0.62 | 8.16 | −0.27 | 1.91 | 0.22 | −4.84 | 0.80 | 8.66 | −9.50 | 1.95 | 0.15 | −5.83 | 0.87 | 25.04 | −9.98 | 21 |
| 5.0 | 2.19 | 0.08 | −6.14 | 0.76 | 16.55 | −0.37 | 2.12 | 0.24 | −5.79 | 0.90 | 17.26 | −10.58 | 2.14 | 0.18 | −6.73 | 0.98 | 31.25 | −10.94 | 22 |
| 5.3 | 2.43 | 0.10 | −7.48 | 0.96 | 28.65 | −0.49 | 2.37 | 0.27 | −7.07 | 1.02 | 29.81 | −11.64 | 2.35 | 0.20 | −7.82 | 1.12 | 38.57 | −11.98 | 23 |
| 5.5 | 2.70 | 0.12 | −9.16 | 1.20 | 44.85 | −0.63 | 2.63 | 0.30 | −8.72 | 1.15 | 46.75 | −12.68 | 2.57 | 0.24 | −9.12 | 1.27 | 47.09 | −13.11 | 24 |
| 5.7 | 2.98 | 0.14 | −11.23 | 1.49 | 65.53 | −0.79 | 2.92 | 0.34 | −10.77 | 1.31 | 68.50 | −13.70 | | | | | | | 25 |
| 6.0 | 3.29 | 0.17 | −13.72 | 1.84 | 91.10 | −0.96 | 3.24 | 0.37 | −13.25 | 1.48 | 95.46 | −14.68 | | | | | | | 26 |
| 6.2 | 3.62 | 0.21 | −16.66 | 2.25 | 121.93 | −1.15 | 3.59 | 0.41 | −16.20 | 1.68 | 128.07 | −15.61 | | | | | | | 27 |
| 6.4 | 3.98 | 0.25 | −20.07 | 2.73 | 158.42 | −1.36 | 3.97 | 0.45 | −19.65 | 1.90 | 166.74 | −16.49 | | | | | | | 28 |
| 6.7 | 4.36 | 0.30 | −24.01 | 3.28 | 200.95 | −1.60 | 4.38 | 0.50 | −23.64 | 2.14 | 211.89 | −17.31 | | | | | | | 29 |
| 6.9 | 4.77 | 0.35 | −28.49 | 3.91 | 249.91 | −1.85 | | | | | | | | | | | | | 30 |

Table E-20: Third unit of three unit seatrain, varied yaw on third unit, rigid mount

| | First Unit 0° Yaw Angle<br>Second Unit 0° Yaw Angle<br>Third Unit 0° Yaw Angle | | | | | | First Unit 0° Yaw Angle<br>Second Unit 0° Yaw Angle<br>Third Unit 5° Yaw Angle | | | | | | First Unit 0° Yaw Angle<br>Second Unit 0° Yaw Angle<br>Third Unit 10° Yaw Angle | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $V_{model}$ | $F_x$ | $F_y$ | $F_z$ | $M_x$ | $M_y$ | $M_z$ | $F_x$ | $F_y$ | $F_z$ | $M_x$ | $M_y$ | $M_z$ | $F_x$ | $F_y$ | $F_z$ | $M_x$ | $M_y$ | $M_z$ | $V_{ship}$ |
| [ft/s] | [lbs] | [lbs] | [lbs] | [in-lbs] | [in-lbs] | [in-lbs] | [lbs] | [lbs] | [lbs] | [in-lbs] | [in-lbs] | [in-lbs] | [lbs] | [lbs] | [lbs] | [in-lbs] | [in-lbs] | [in-lbs] | [kts] |
| 2.3 | 0.51 | −0.05 | −1.85 | 0.04 | 41.45 | −3.12 | 0.57 | −0.22 | −5.88 | −5.53 | 42.71 | 19.07 | 0.63 | −0.90 | −4.15 | −5.76 | 4.71 | 33.05 | 10 |
| 2.5 | 0.59 | −0.04 | −1.99 | 0.07 | 36.43 | −2.57 | 0.67 | −0.36 | −5.65 | −5.46 | 37.60 | 22.12 | 0.76 | −1.07 | −4.21 | −6.59 | 4.14 | 39.05 | 11 |
| 2.8 | 0.69 | −0.03 | −2.14 | 0.09 | 31.00 | −1.96 | 0.77 | −0.51 | −5.38 | −5.39 | 32.07 | 25.46 | 0.90 | −1.27 | −4.29 | −7.53 | 3.63 | 45.91 | 12 |
| 3.0 | 0.80 | −0.02 | −2.30 | 0.11 | 25.49 | −1.31 | 0.89 | −0.68 | −5.11 | −5.33 | 26.43 | 29.12 | 1.07 | −1.50 | −4.41 | −8.59 | 3.27 | 53.71 | 13 |
| 3.2 | 0.91 | −0.01 | −2.46 | 0.11 | 20.20 | −0.64 | 1.02 | −0.85 | −4.87 | −5.31 | 21.00 | 33.12 | 1.24 | −1.76 | −4.57 | −9.79 | 3.10 | 62.54 | 14 |
| 3.4 | 1.04 | 0.00 | −2.64 | 0.10 | 15.46 | 0.01 | 1.17 | −1.04 | −4.68 | −5.36 | 16.09 | 37.48 | 1.44 | −2.05 | −4.81 | −11.15 | 3.20 | 72.50 | 15 |
| 3.7 | 1.17 | 0.01 | −2.83 | 0.08 | 11.58 | 0.63 | 1.32 | −1.24 | −4.59 | −5.50 | 12.03 | 42.22 | 1.65 | −2.37 | −5.14 | −12.68 | 3.64 | 83.68 | 16 |
| 3.9 | 1.32 | 0.02 | −3.04 | 0.05 | 8.88 | 1.19 | 1.49 | −1.44 | −4.61 | −5.76 | 9.14 | 47.36 | 1.89 | −2.73 | −5.59 | −14.39 | 4.47 | 96.17 | 17 |
| 4.1 | 1.48 | 0.03 | −3.28 | −0.01 | 7.67 | 1.67 | 1.67 | −1.64 | −4.77 | −6.16 | 7.74 | 52.92 | 2.14 | −3.13 | −6.16 | −16.31 | 5.77 | 110.06 | 18 |
| 4.4 | 1.65 | 0.04 | −3.53 | −0.08 | 8.28 | 2.04 | 1.87 | −1.85 | −5.11 | −6.73 | 8.14 | 58.93 | 2.41 | −3.57 | −6.88 | −18.45 | 7.60 | 125.43 | 19 |
| 4.6 | 1.83 | 0.05 | −3.82 | −0.18 | 11.02 | 2.28 | 2.08 | −2.05 | −5.66 | −7.50 | 10.67 | 65.41 | 2.70 | −4.05 | −7.78 | −20.82 | 10.02 | 142.39 | 20 |
| 4.8 | 2.03 | 0.05 | −4.13 | −0.31 | 16.19 | 2.36 | 2.31 | −2.26 | −6.44 | −8.48 | 15.64 | 72.37 | 3.01 | −4.58 | −8.86 | −23.45 | 13.11 | 161.03 | 21 |
| 5.0 | 2.24 | 0.05 | −4.48 | −0.46 | 24.13 | 2.26 | 2.55 | −2.46 | −7.49 | −9.71 | 23.37 | 79.85 | 3.35 | −5.16 | −10.16 | −26.33 | 16.93 | 181.43 | 22 |
| 5.3 | 2.46 | 0.05 | −4.86 | −0.64 | 35.15 | 1.96 | 2.81 | −2.66 | −8.83 | −11.21 | 34.19 | 87.86 | 3.70 | −5.79 | −11.68 | −29.50 | 21.54 | 203.68 | 23 |
| 5.5 | 2.70 | 0.05 | −5.28 | −0.85 | 49.56 | 1.44 | 3.09 | −2.85 | −10.50 | −13.01 | 48.41 | 96.41 | 4.08 | −6.46 | −13.45 | −32.97 | 27.01 | 227.89 | 24 |
| 5.7 | 2.95 | 0.04 | −5.75 | −1.09 | 67.69 | 0.66 | 3.38 | −3.04 | −12.52 | −15.13 | 66.35 | 105.55 | | | | | | | 25 |
| 6.0 | 3.22 | 0.04 | −6.26 | −1.38 | 89.84 | −0.40 | 3.70 | −3.21 | −14.92 | −17.60 | 88.34 | 115.28 | | | | | | | 26 |
| 6.2 | 3.50 | 0.02 | −6.81 | −1.70 | 116.33 | −1.75 | 4.03 | −3.37 | −17.74 | −20.44 | 114.68 | 125.63 | | | | | | | 27 |
| 6.4 | 3.80 | 0.00 | −7.42 | −2.06 | 147.48 | −3.43 | 4.39 | −3.52 | −21.00 | −23.68 | 145.71 | 136.61 | | | | | | | 28 |
| 6.7 | 4.12 | −0.02 | −8.07 | −2.46 | 183.61 | −5.46 | 4.76 | −3.65 | −24.73 | −27.34 | 181.73 | 148.26 | | | | | | | 29 |
| 6.9 | 4.45 | −0.04 | −8.79 | −2.91 | 225.04 | −7.86 | | | | | | | | | | | | | 30 |

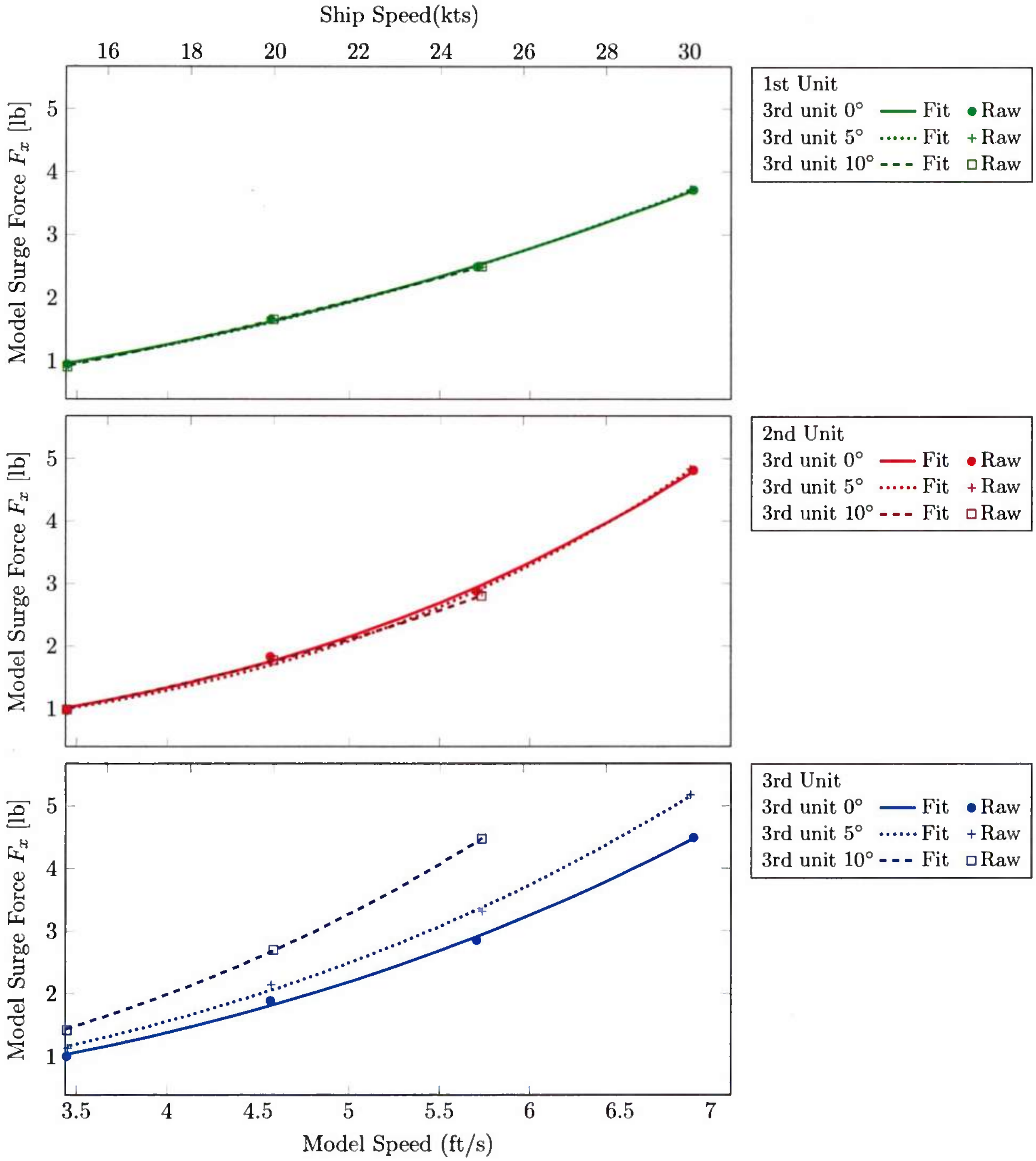



**Figure E-26: Surge force, three unit seatrain, varied yaw on third unit, rigid mount**

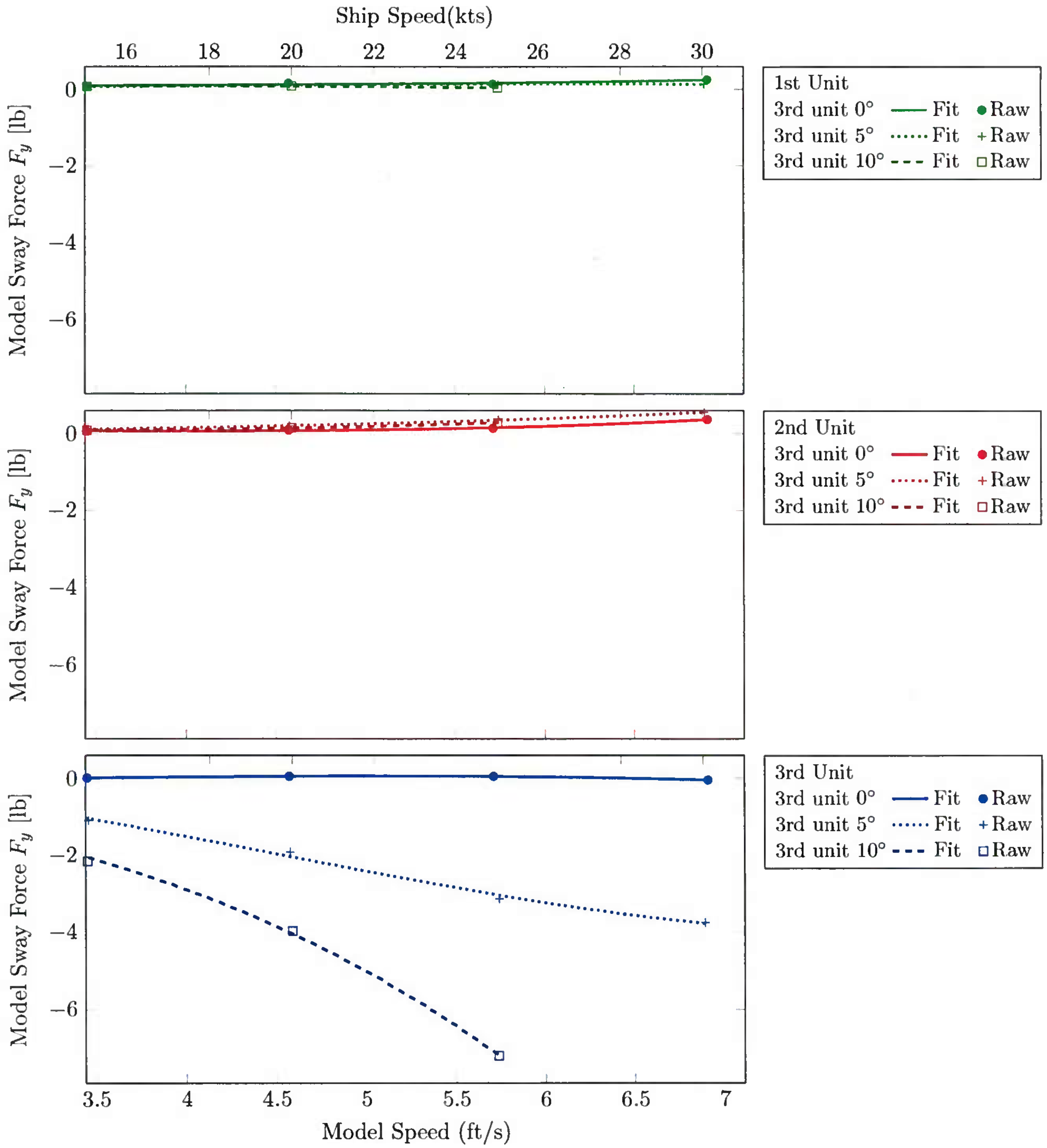



**Figure E-27: Sway force, three unit seatrain, varied yaw on third unit, rigid mount**

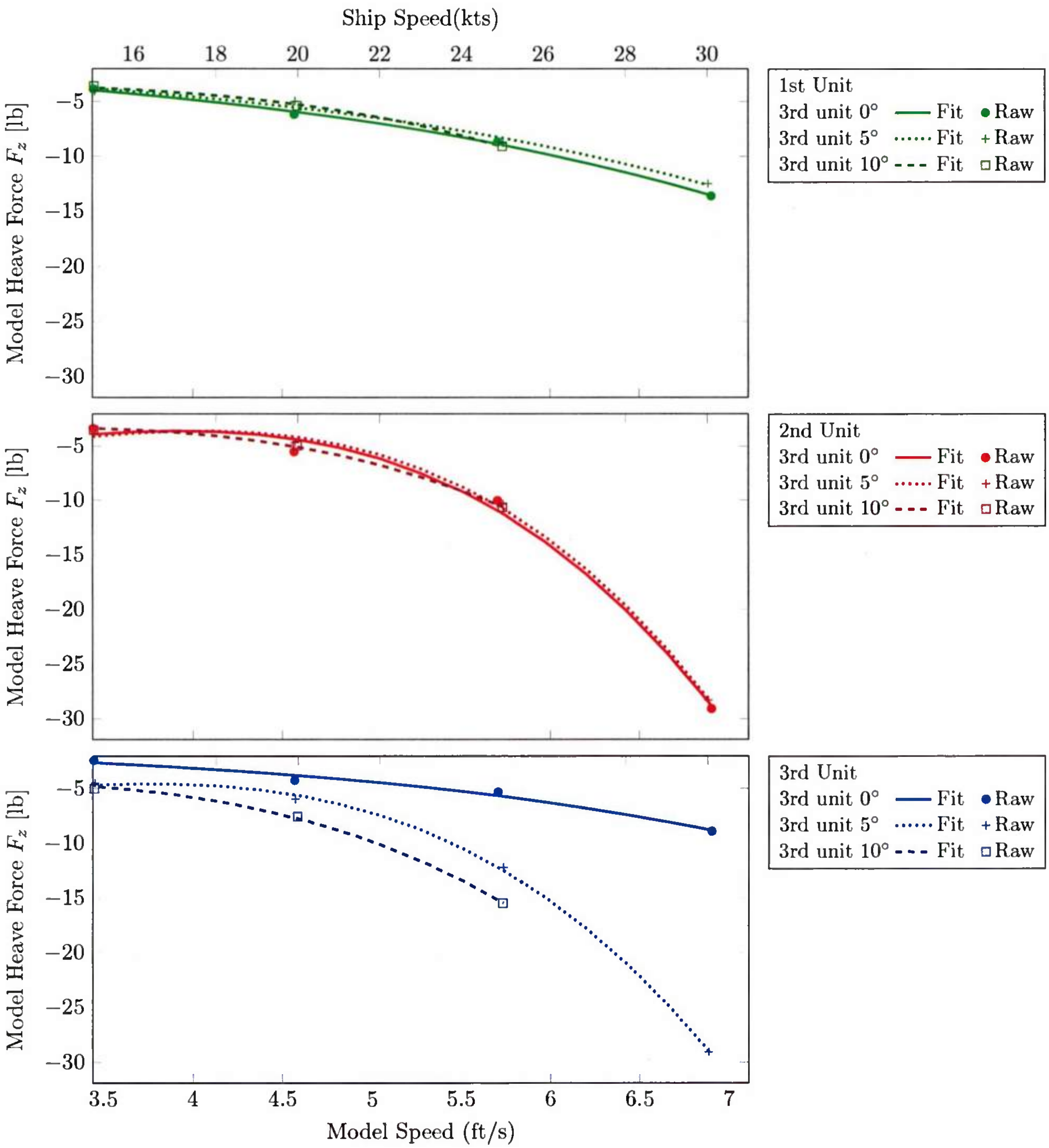



**Figure E-28: Heave force, three unit seatrain, varied yaw on third unit, rigid mount**

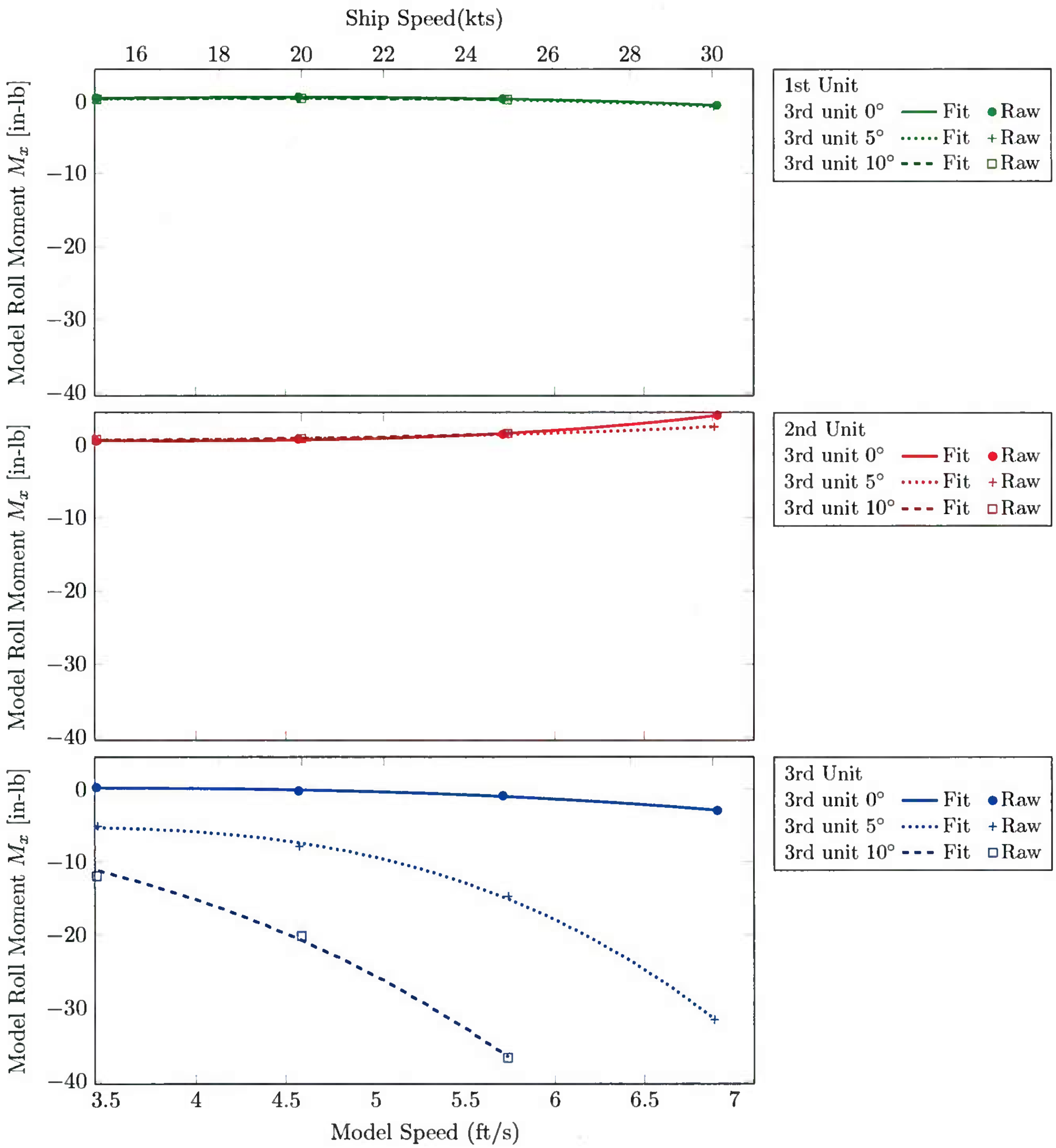



**Figure E-29: Roll moment, three unit seatrain, varied yaw on third unit, rigid mount**

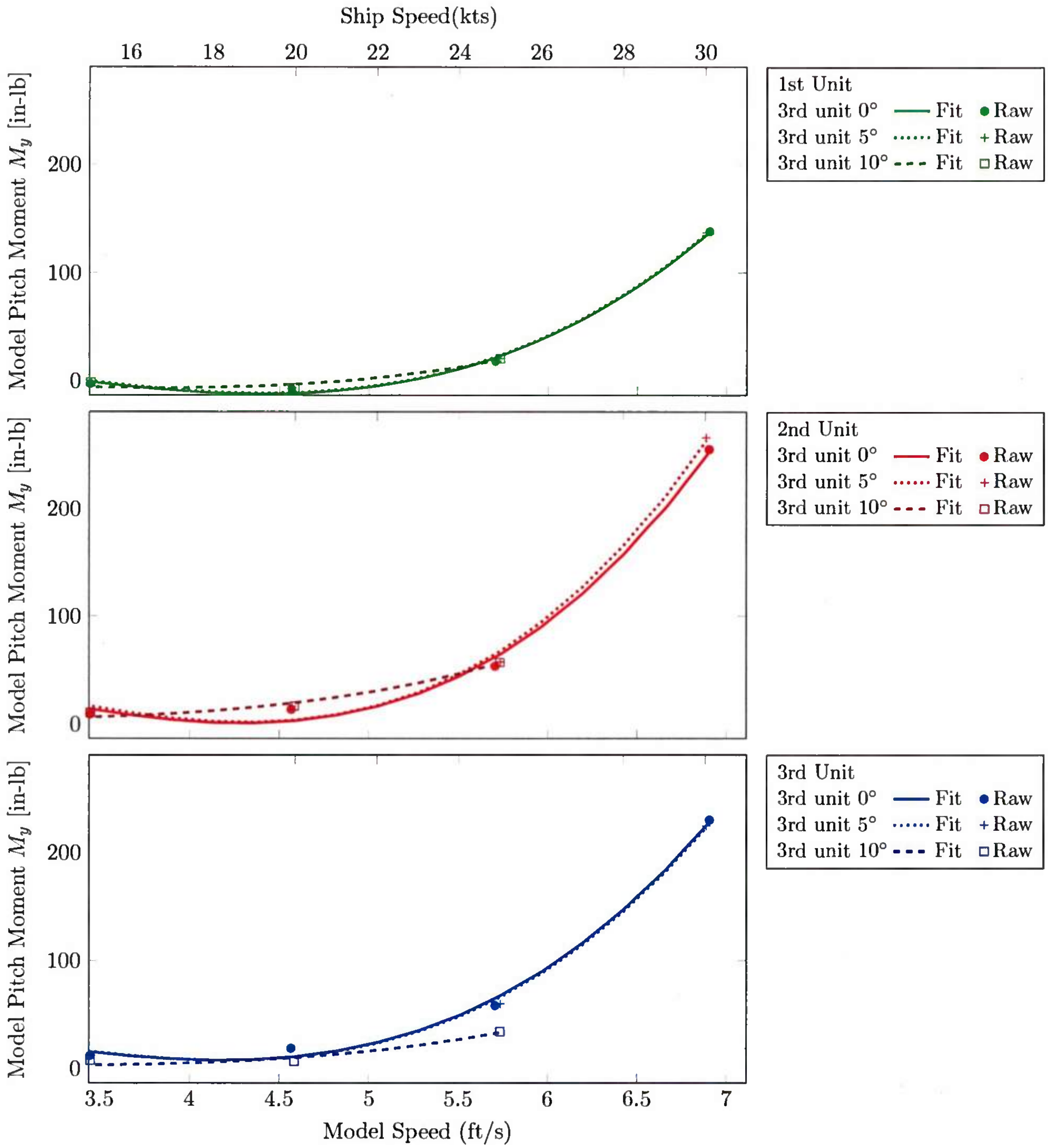



**Figure E-30: Pitch moment, three unit seatrain, varied yaw on third unit, rigid mount**

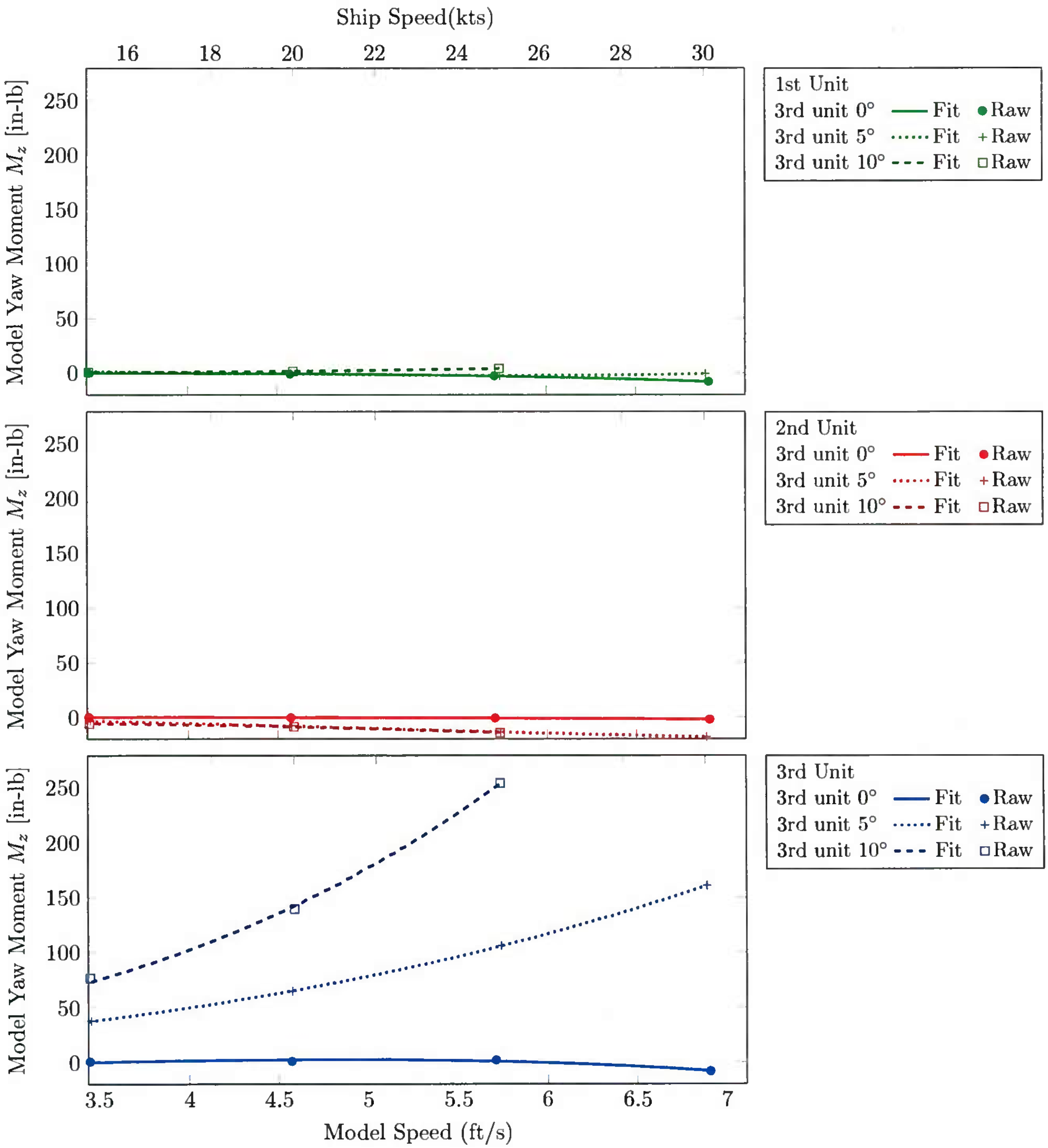



**Figure E-31: Yaw moment, three unit seatrain, varied yaw on third unit, rigid mount**

## Three Unit Seatrain, Varied Yaw on First and Third Unit, Rigid Mount, Tests 17, 22 and 23

**Table E-21: First unit of three unit seatrain, varied yaw on first unit and third unit, rigid mount**

| | First Unit 0° Yaw Angle<br>Second Unit 0° Yaw Angle<br>Third Unit 0° Yaw Angle | | | | | | First Unit 5° Yaw Angle<br>Second Unit 0° Yaw Angle<br>Third Unit 5° Yaw Angle | | | | | | First Unit 10° Yaw Angle<br>Second Unit 0° Yaw Angle<br>Third Unit 10° Yaw Angle | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $V_{model}$ [ft/s] | $F_x$ [lbs] | $F_y$ [lbs] | $F_z$ [lbs] | $M_x$ [in-lbs] | $M_y$ [in-lbs] | $M_z$ [in-lbs] | $F_x$ [lbs] | $F_y$ [lbs] | $F_z$ [lbs] | $M_x$ [in-lbs] | $M_y$ [in-lbs] | $M_z$ [in-lbs] | $F_x$ [lbs] | $F_y$ [lbs] | $F_z$ [lbs] | $M_x$ [in-lbs] | $M_y$ [in-lbs] | $M_z$ [in-lbs] | $V_{ship}$ [kts] |
| 2.3 | 0.46 | 0.08 | −2.63 | 0.05 | 24.72 | −0.69 | 0.47 | 0.46 | −1.68 | 0.83 | −2.14 | −19.95 | 0.63 | 1.08 | −2.99 | 1.98 | −8.28 | −50.30 | 10 |
| 2.5 | 0.55 | 0.09 | −2.87 | 0.11 | 19.79 | −0.61 | 0.58 | 0.61 | −2.11 | 0.83 | −4.00 | −23.72 | 0.76 | 1.30 | −3.84 | 2.45 | −9.25 | −61.74 | 11 |
| 2.8 | 0.64 | 0.09 | −3.12 | 0.17 | 14.50 | −0.53 | 0.70 | 0.77 | −2.58 | 0.84 | −5.84 | −27.97 | 0.89 | 1.54 | −4.73 | 2.91 | −10.40 | −74.28 | 12 |
| 3.0 | 0.74 | 0.09 | −3.39 | 0.23 | 9.09 | −0.46 | 0.82 | 0.94 | −3.09 | 0.86 | −7.59 | −32.73 | 1.05 | 1.82 | −5.65 | 3.34 | −11.75 | −87.89 | 13 |
| 3.2 | 0.84 | 0.10 | −3.68 | 0.29 | 3.79 | −0.40 | 0.96 | 1.12 | −3.63 | 0.89 | −9.16 | −38.05 | 1.22 | 2.12 | −6.57 | 3.73 | −13.35 | −102.55 | 14 |
| 3.4 | 0.96 | 0.10 | −3.98 | 0.35 | −1.14 | −0.37 | 1.11 | 1.31 | −4.20 | 0.94 | −10.47 | −43.95 | 1.41 | 2.46 | −7.48 | 4.06 | −15.22 | −118.24 | 15 |
| 3.7 | 1.08 | 0.11 | −4.31 | 0.40 | −5.46 | −0.37 | 1.26 | 1.50 | −4.81 | 1.02 | −11.43 | −50.48 | 1.62 | 2.84 | −8.37 | 4.33 | −17.42 | −134.95 | 16 |
| 3.9 | 1.21 | 0.11 | −4.67 | 0.44 | −8.92 | −0.41 | 1.42 | 1.69 | −5.44 | 1.13 | −11.98 | −57.68 | 1.86 | 3.25 | −9.22 | 4.50 | −19.97 | −152.66 | 17 |
| 4.1 | 1.34 | 0.12 | −5.06 | 0.48 | −11.28 | −0.49 | 1.59 | 1.88 | −6.10 | 1.28 | −12.03 | −65.58 | 2.11 | 3.70 | −10.01 | 4.58 | −22.90 | −171.34 | 18 |
| 4.4 | 1.49 | 0.13 | −5.48 | 0.50 | −12.31 | −0.63 | 1.76 | 2.07 | −6.78 | 1.46 | −11.50 | −74.22 | 2.40 | 4.19 | −10.74 | 4.53 | −26.26 | −190.98 | 19 |
| 4.6 | 1.64 | 0.13 | −5.95 | 0.51 | −11.74 | −0.82 | 1.94 | 2.26 | −7.48 | 1.69 | −10.30 | −83.65 | | | | | | | 20 |
| 4.8 | 1.81 | 0.14 | −6.45 | 0.50 | −9.34 | −1.09 | 2.13 | 2.45 | −8.20 | 1.97 | −8.37 | −93.89 | | | | | | | 21 |
| 5.0 | 1.98 | 0.15 | −7.00 | 0.47 | −4.87 | −1.43 | 2.33 | 2.63 | −8.93 | 2.31 | −5.61 | −104.99 | | | | | | | 22 |
| 5.3 | 2.16 | 0.16 | −7.60 | 0.43 | 1.93 | −1.85 | 2.53 | 2.80 | −9.68 | 2.70 | −1.95 | −116.99 | | | | | | | 23 |
| 5.5 | 2.35 | 0.17 | −8.25 | 0.36 | 11.29 | −2.36 | 2.74 | 2.96 | −10.45 | 3.16 | 2.69 | −129.92 | | | | | | | 24 |
| 5.7 | 2.55 | 0.18 | −8.96 | 0.27 | 23.47 | −2.97 | 2.95 | 3.11 | −11.22 | 3.70 | 8.40 | −143.82 | | | | | | | 25 |
| 6.0 | 2.76 | 0.19 | −9.72 | 0.15 | 38.70 | −3.68 | | | | | | | | | | | | | 26 |
| 6.2 | 2.98 | 0.20 | −10.55 | 0.01 | 57.23 | −4.51 | | | | | | | | | | | | | 27 |
| 6.4 | 3.21 | 0.21 | −11.45 | −0.16 | 79.30 | −5.45 | | | | | | | | | | | | | 28 |
| 6.7 | 3.44 | 0.23 | −12.41 | −0.37 | 105.16 | −6.52 | | | | | | | | | | | | | 29 |
| 6.9 | 3.69 | 0.25 | −13.45 | −0.61 | 135.05 | −7.73 | | | | | | | | | | | | | 30 |

Table E-22: Second unit of three unit seatrain, varied yaw on first unit and third unit, rigid mount

| | First Unit 0° Yaw Angle Second Unit 0° Yaw Angle Third Unit 0° Yaw Angle | | | | | | First Unit 5° Yaw Angle Second Unit 0° Yaw Angle Third Unit 5° Yaw Angle | | | | | | First Unit 10° Yaw Angle Second Unit 0° Yaw Angle Third Unit 10° Yaw Angle | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $V_{model}$ [ft/s] | $F_x$ [lbs] | $F_y$ [lbs] | $F_z$ [lbs] | $M_x$ [in-lbs] | $M_y$ [in-lbs] | $M_z$ [in-lbs] | $F_x$ [lbs] | $F_y$ [lbs] | $F_z$ [lbs] | $M_x$ [in-lbs] | $M_y$ [in-lbs] | $M_z$ [in-lbs] | $F_x$ [lbs] | $F_y$ [lbs] | $F_z$ [lbs] | $M_x$ [in-lbs] | $M_y$ [in-lbs] | $M_z$ [in-lbs] | $V_{ship}$ [kts] |
| 2.3 | 0.55 | 0.07 | −5.74 | 0.67 | 49.44 | 0.13 | 0.44 | −0.25 | −1.21 | −0.50 | 5.22 | 8.47 | 0.45 | −0.68 | −1.36 | −1.32 | 2.73 | 16.98 | 10 |
| 2.5 | 0.63 | 0.06 | −5.39 | 0.62 | 42.70 | 0.14 | 0.54 | −0.34 | −1.46 | −0.61 | 4.42 | 10.95 | 0.55 | −0.79 | −2.06 | −1.45 | 3.85 | 20.07 | 11 |
| 2.8 | 0.71 | 0.06 | −5.00 | 0.56 | 35.40 | 0.14 | 0.65 | −0.44 | −1.75 | −0.72 | 3.76 | 13.64 | 0.66 | −0.91 | −2.76 | −1.61 | 5.02 | 23.72 | 12 |
| 3.0 | 0.80 | 0.05 | −4.61 | 0.51 | 27.91 | 0.13 | 0.76 | −0.55 | −2.08 | −0.82 | 3.34 | 16.51 | 0.78 | −1.06 | −3.46 | −1.82 | 6.22 | 27.99 | 13 |
| 3.2 | 0.90 | 0.05 | −4.24 | 0.46 | 20.63 | 0.11 | 0.89 | −0.65 | −2.45 | −0.91 | 3.24 | 19.54 | 0.90 | −1.23 | −4.11 | −2.10 | 7.42 | 32.96 | 14 |
| 3.4 | 1.01 | 0.05 | −3.93 | 0.42 | 13.94 | 0.09 | 1.03 | −0.76 | −2.88 | −0.98 | 3.58 | 22.69 | 1.04 | −1.43 | −4.70 | −2.45 | 8.60 | 38.72 | 15 |
| 3.7 | 1.13 | 0.05 | −3.71 | 0.39 | 8.25 | 0.06 | 1.18 | −0.87 | −3.35 | −1.02 | 4.43 | 25.94 | 1.18 | −1.66 | −5.20 | −2.88 | 9.73 | 45.32 | 16 |
| 3.9 | 1.27 | 0.05 | −3.61 | 0.38 | 3.92 | 0.02 | 1.33 | −0.98 | −3.88 | −1.05 | 5.91 | 29.28 | 1.32 | −1.93 | −5.59 | −3.41 | 10.79 | 52.84 | 17 |
| 4.1 | 1.42 | 0.05 | −3.68 | 0.40 | 1.36 | −0.03 | 1.50 | −1.08 | −4.47 | −1.04 | 8.09 | 32.67 | 1.48 | −2.23 | −5.85 | −4.05 | 11.75 | 61.37 | 18 |
| 4.4 | 1.59 | 0.05 | −3.93 | 0.44 | 0.96 | −0.10 | 1.68 | −1.18 | −5.12 | −1.00 | 11.09 | 36.09 | 1.64 | −2.58 | −5.95 | −4.80 | 12.59 | 70.97 | 19 |
| 4.6 | 1.77 | 0.06 | −4.40 | 0.51 | 3.09 | −0.18 | 1.87 | −1.27 | −5.84 | −0.93 | 14.99 | 39.51 | | | | | | | 20 |
| 4.8 | 1.97 | 0.07 | −5.13 | 0.62 | 8.16 | −0.27 | 2.07 | −1.35 | −6.63 | −0.81 | 19.90 | 42.92 | | | | | | | 21 |
| 5.0 | 2.19 | 0.08 | −6.14 | 0.76 | 16.55 | −0.37 | 2.28 | −1.42 | −7.49 | −0.64 | 25.90 | 46.29 | | | | | | | 22 |
| 5.3 | 2.43 | 0.10 | −7.48 | 0.96 | 28.65 | −0.49 | 2.50 | −1.48 | −8.43 | −0.43 | 33.10 | 49.58 | | | | | | | 23 |
| 5.5 | 2.70 | 0.12 | −9.16 | 1.20 | 44.85 | −0.63 | 2.73 | −1.52 | −9.44 | −0.16 | 41.58 | 52.79 | | | | | | | 24 |
| 5.7 | 2.98 | 0.14 | −11.23 | 1.49 | 65.53 | −0.79 | 2.97 | −1.55 | −10.55 | 0.17 | 51.45 | 55.87 | | | | | | | 25 |
| 6.0 | 3.29 | 0.17 | −13.72 | 1.84 | 91.10 | −0.96 | | | | | | | | | | | | | 26 |
| 6.2 | 3.62 | 0.21 | −16.66 | 2.25 | 121.93 | −1.15 | | | | | | | | | | | | | 27 |
| 6.4 | 3.98 | 0.25 | −20.07 | 2.73 | 158.42 | −1.36 | | | | | | | | | | | | | 28 |
| 6.7 | 4.36 | 0.30 | −24.01 | 3.28 | 200.95 | −1.60 | | | | | | | | | | | | | 29 |
| 6.9 | 4.77 | 0.35 | −28.49 | 3.91 | 249.91 | −1.85 | | | | | | | | | | | | | 30 |

Table E-23: Third unit of three unit seatrain, varied yaw on first unit and third unit, rigid mount

| | First Unit 0° Yaw Angle, Second Unit 0° Yaw Angle, Third Unit 0° Yaw Angle | | | | | | First Unit 5° Yaw Angle, Second Unit 0° Yaw Angle, Third Unit 5° Yaw Angle | | | | | | First Unit 10° Yaw Angle, Second Unit 0° Yaw Angle, Third Unit 10° Yaw Angle | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $V_{model}$ | $F_x$ | $F_y$ | $F_z$ | $M_x$ | $M_y$ | $M_z$ | $F_x$ | $F_y$ | $F_z$ | $M_x$ | $M_y$ | $M_z$ | $F_x$ | $F_y$ | $F_z$ | $M_x$ | $M_y$ | $M_z$ | $V_{ship}$ |
| [ft/s] | [lbs] | [lbs] | [lbs] | [in-lbs] | [in-lbs] | [in-lbs] | [lbs] | [lbs] | [lbs] | [in-lbs] | [in-lbs] | [in-lbs] | [lbs] | [lbs] | [lbs] | [in-lbs] | [in-lbs] | [in-lbs] | [kts] |
| 2.3 | 0.51 | −0.05 | −1.85 | 0.04 | 41.45 | −3.12 | 0.04 | −0.04 | −1.33 | −0.57 | 0.06 | 19.06 | 0.67 | −1.11 | −1.58 | −5.81 | 0.44 | 37.36 | 10 |
| 2.5 | 0.59 | −0.04 | −1.99 | 0.07 | 36.43 | −2.57 | 0.01 | 0.00 | −1.71 | −0.51 | −0.94 | 23.35 | 0.80 | −1.33 | −2.50 | −7.24 | 1.62 | 46.61 | 11 |
| 2.8 | 0.69 | −0.03 | −2.14 | 0.09 | 31.00 | −1.96 | −0.01 | 0.04 | −2.12 | −0.49 | −1.80 | 27.99 | 0.95 | −1.57 | −3.45 | −8.76 | 2.74 | 56.51 | 12 |
| 3.0 | 0.80 | −0.02 | −2.30 | 0.11 | 25.49 | −1.31 | −0.02 | 0.07 | −2.59 | −0.52 | −2.43 | 32.97 | 1.11 | −1.84 | −4.37 | −10.35 | 3.72 | 66.98 | 13 |
| 3.2 | 0.91 | −0.01 | −2.46 | 0.11 | 20.20 | −0.64 | −0.01 | 0.08 | −3.10 | −0.62 | −2.77 | 38.27 | 1.29 | −2.13 | −5.26 | −11.99 | 4.49 | 77.93 | 14 |
| 3.4 | 1.04 | 0.00 | −2.64 | 0.10 | 15.46 | 0.01 | 0.01 | 0.08 | −3.66 | −0.79 | −2.72 | 43.88 | 1.49 | −2.45 | −6.07 | −13.68 | 4.98 | 89.26 | 15 |
| 3.7 | 1.17 | 0.01 | −2.83 | 0.08 | 11.58 | 0.63 | 0.06 | 0.05 | −4.27 | −1.06 | −2.20 | 49.76 | 1.71 | −2.80 | −6.78 | −15.39 | 5.14 | 100.91 | 16 |
| 3.9 | 1.32 | 0.02 | −3.04 | 0.05 | 8.88 | 1.19 | 0.13 | 0.00 | −4.93 | −1.44 | −1.14 | 55.91 | 1.95 | −3.17 | −7.35 | −17.10 | 4.88 | 112.76 | 17 |
| 4.1 | 1.48 | 0.03 | −3.28 | −0.01 | 7.67 | 1.67 | 0.24 | −0.07 | −5.64 | −1.94 | 0.55 | 62.30 | 2.20 | −3.58 | −7.76 | −18.81 | 4.14 | 124.75 | 18 |
| 4.4 | 1.65 | 0.04 | −3.53 | −0.08 | 8.28 | 2.04 | 0.37 | −0.18 | −6.40 | −2.58 | 2.95 | 68.92 | 2.48 | −4.02 | −7.97 | −20.48 | 2.85 | 136.78 | 19 |
| 4.6 | 1.83 | 0.05 | −3.82 | −0.18 | 11.02 | 2.28 | 0.55 | −0.33 | −7.22 | −3.37 | 6.15 | 75.75 | | | | | | | 20 |
| 4.8 | 2.03 | 0.05 | −4.13 | −0.31 | 16.19 | 2.36 | 0.76 | −0.51 | −8.09 | −4.33 | 10.21 | 82.76 | | | | | | | 21 |
| 5.0 | 2.24 | 0.05 | −4.48 | −0.46 | 24.13 | 2.26 | 1.02 | −0.74 | −9.02 | −5.47 | 15.23 | 89.95 | | | | | | | 22 |
| 5.3 | 2.46 | 0.05 | −4.86 | −0.64 | 35.15 | 1.96 | 1.33 | −1.01 | −10.00 | −6.80 | 21.28 | 97.28 | | | | | | | 23 |
| 5.5 | 2.70 | 0.05 | −5.28 | −0.85 | 49.56 | 1.44 | 1.68 | −1.34 | −11.05 | −8.34 | 28.45 | 104.74 | | | | | | | 24 |
| 5.7 | 2.95 | 0.04 | −5.75 | −1.09 | 67.69 | 0.66 | 2.10 | −1.72 | −12.15 | −10.10 | 36.82 | 112.32 | | | | | | | 25 |
| 6.0 | 3.22 | 0.04 | −6.26 | −1.38 | 89.84 | −0.40 | | | | | | | | | | | | | 26 |
| 6.2 | 3.50 | 0.02 | −6.81 | −1.70 | 116.33 | −1.75 | | | | | | | | | | | | | 27 |
| 6.4 | 3.80 | 0.00 | −7.42 | −2.06 | 147.48 | −3.43 | | | | | | | | | | | | | 28 |
| 6.7 | 4.12 | −0.02 | −8.07 | −2.46 | 183.61 | −5.46 | | | | | | | | | | | | | 29 |
| 6.9 | 4.45 | −0.04 | −8.79 | −2.91 | 225.04 | −7.86 | | | | | | | | | | | | | 30 |

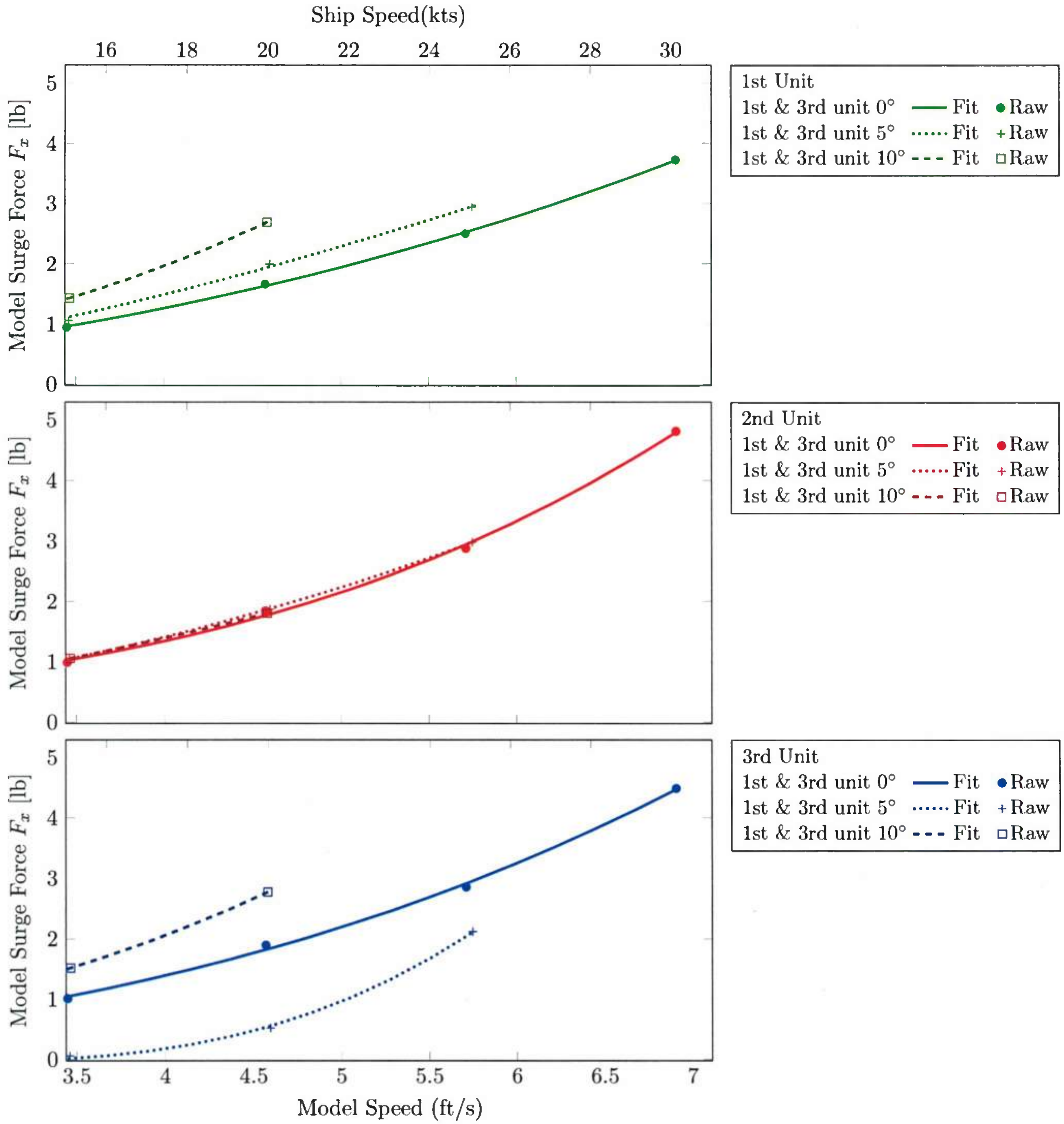



**Figure E-32: Surge force, three unit seatrain, varied yaw on first unit and third unit, rigid mount**

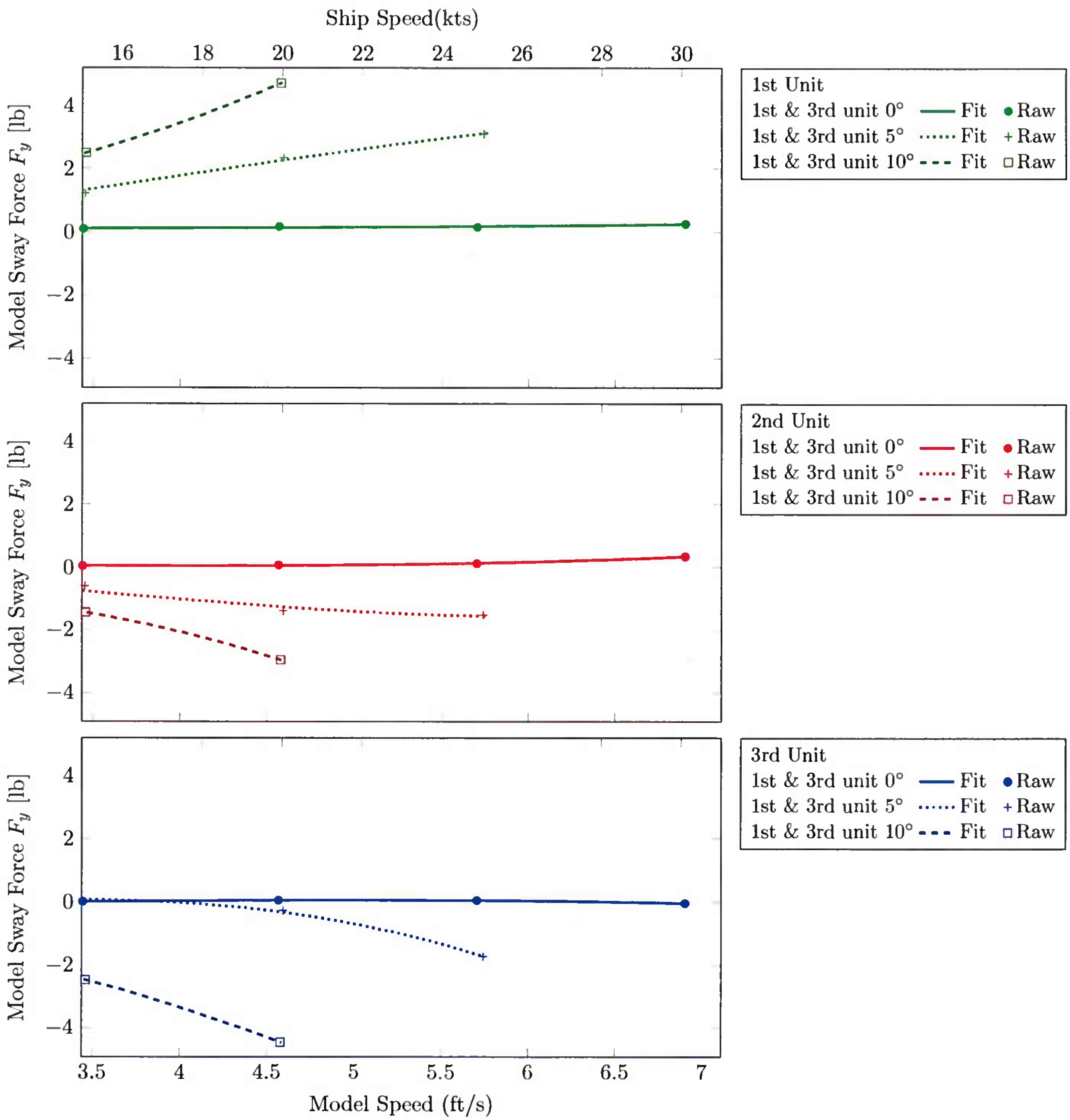



**Figure E-33: Sway force, three unit seatrain, varied yaw on first unit and third unit, rigid mount**

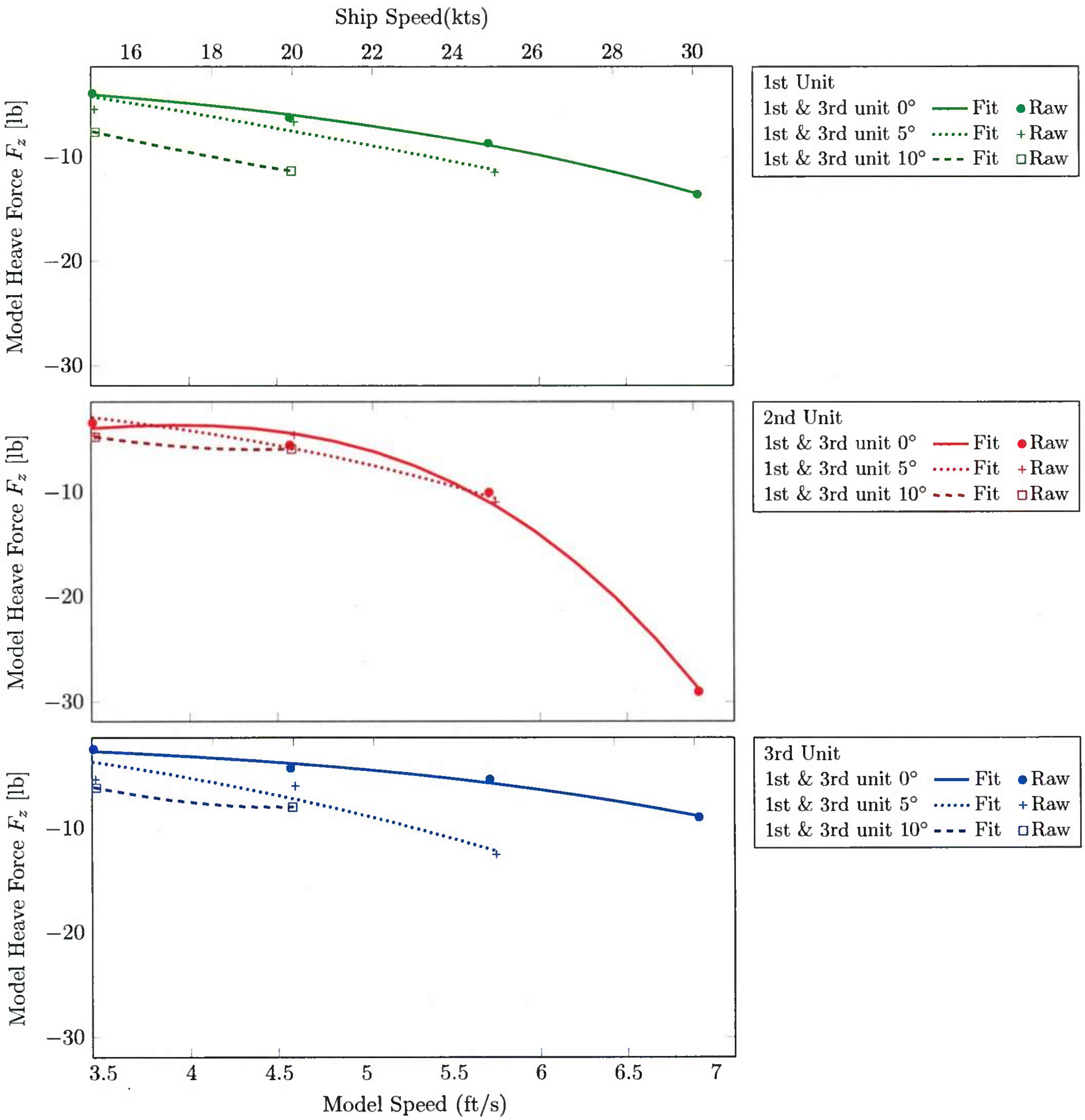



**Figure E-34: Heave force, three unit seatrain, varied yaw on first unit and third unit, rigid mount**

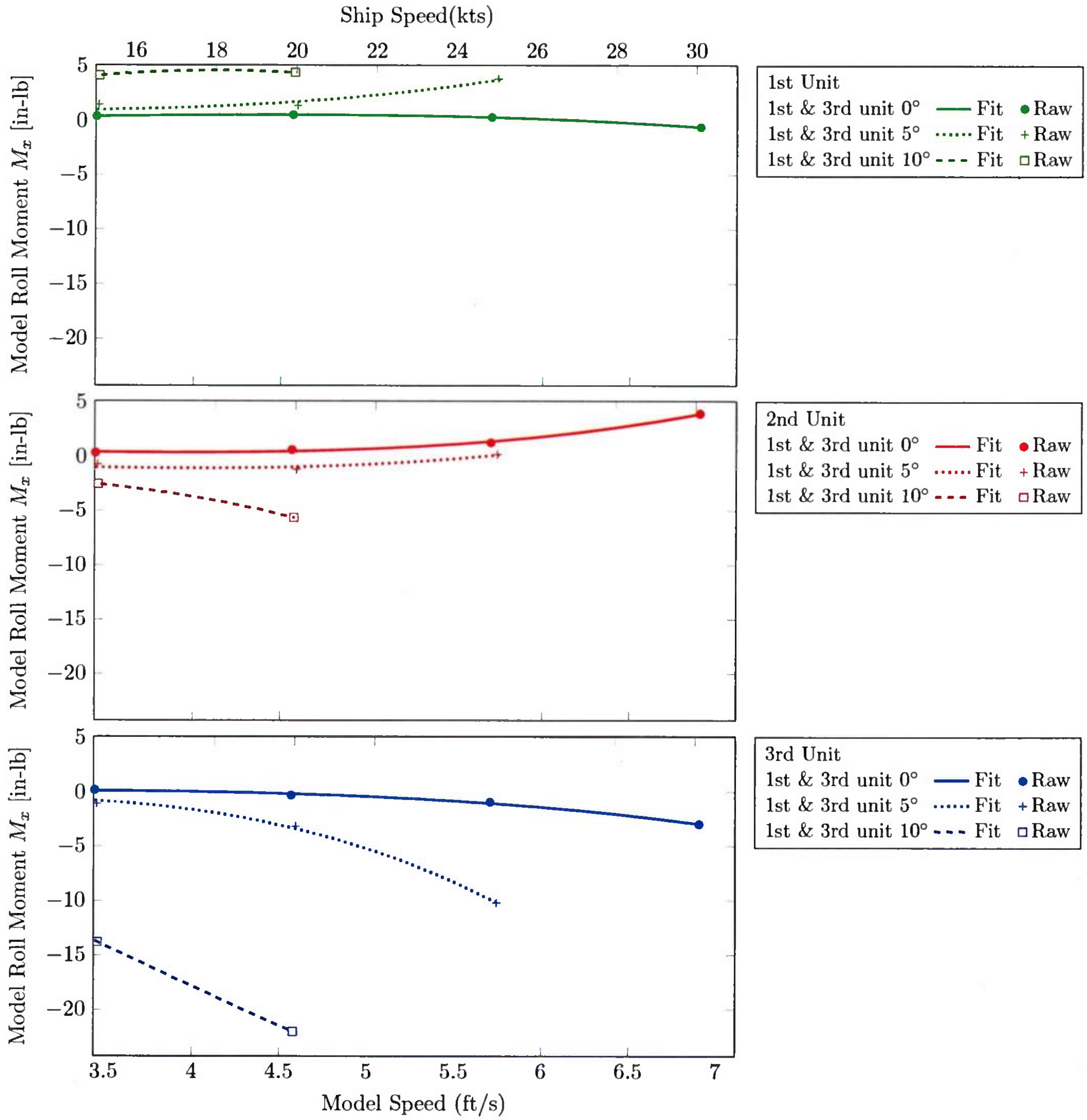



**Figure E-35: Roll moment, three unit seatrain, varied yaw on first unit and third unit, rigid mount**

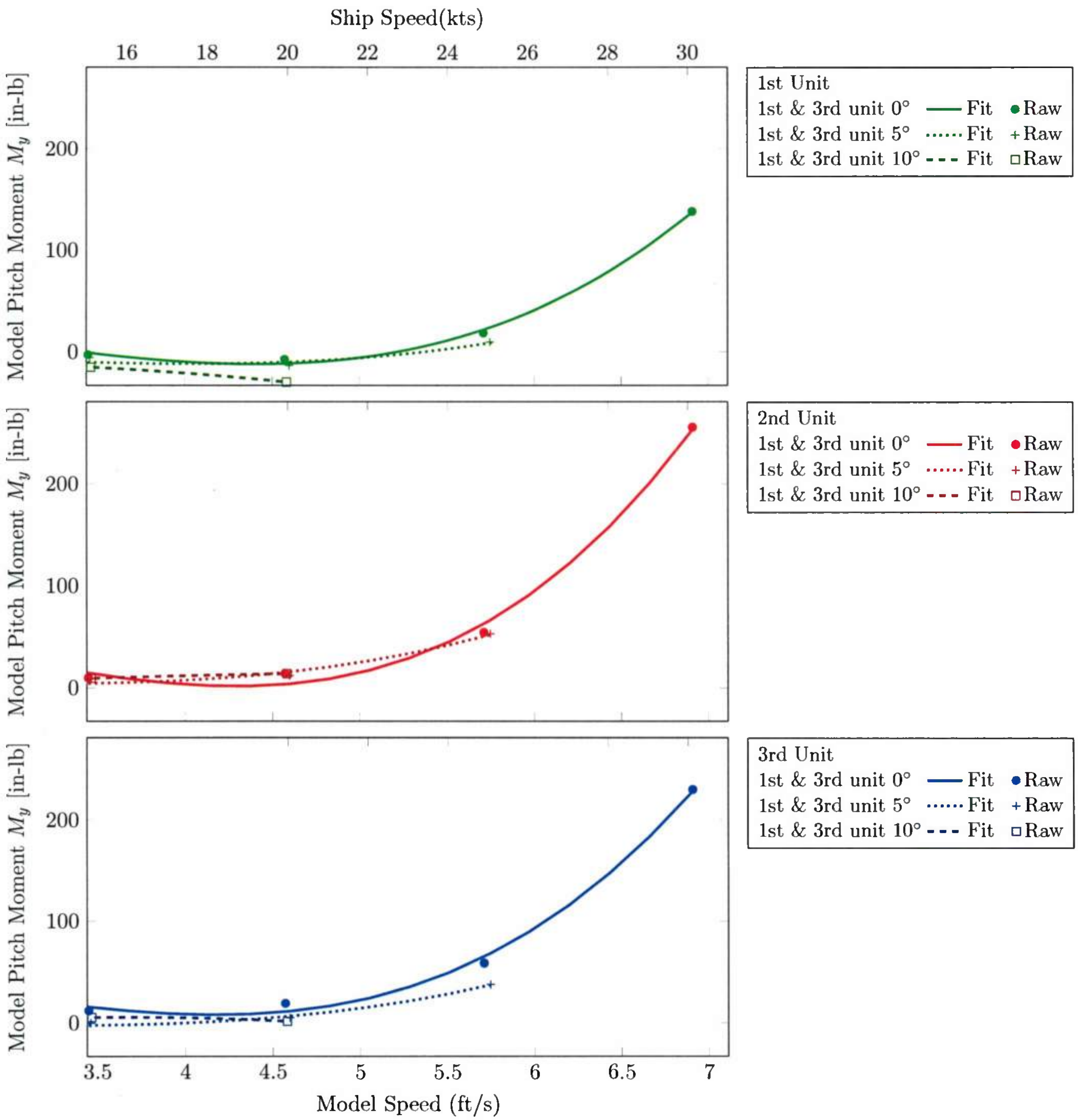



**Figure E-36: Pitch moment, three unit seatrain, varied yaw on first unit and third unit, rigid mount**

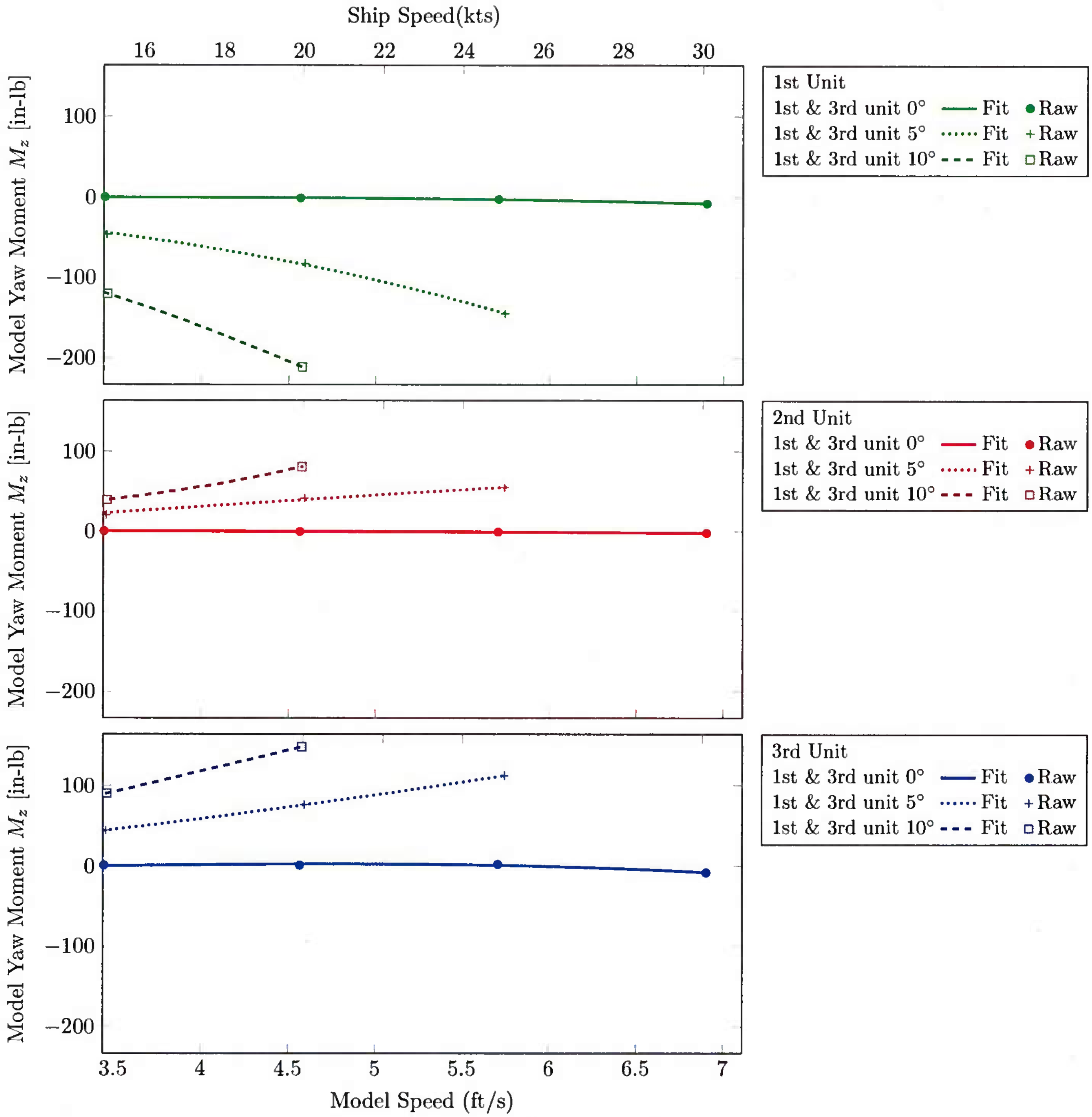



**Figure E-37: Yaw moment, three unit seatrain, varied yaw on first unit and third unit, rigid mount**

# APPENDIX F: TURNING DEMONSTRATION

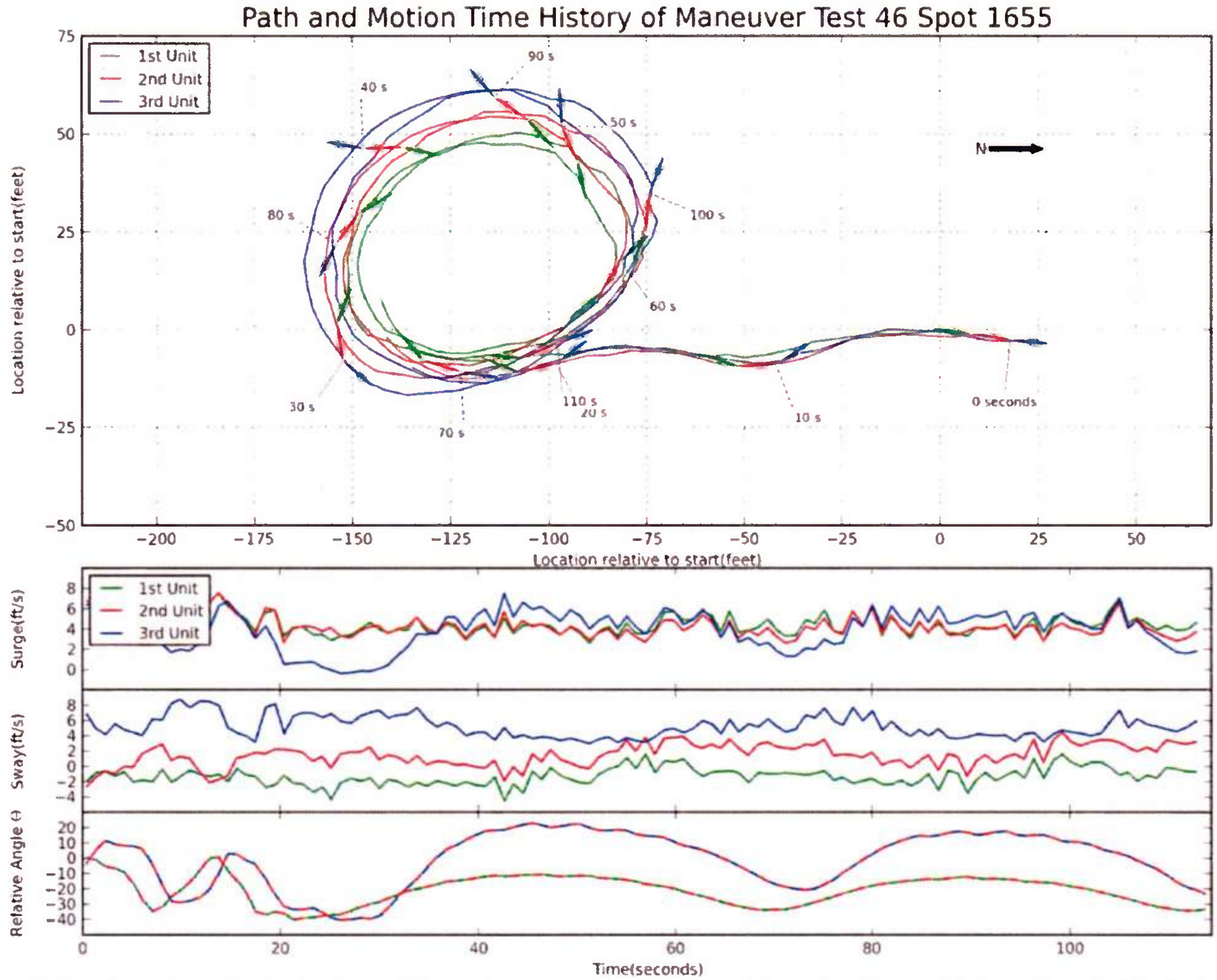



**Figure F-1: Turning circle test, 6 ft/s entry speed, turning diameter 9.1 unit lengths, 2-D plot and data**

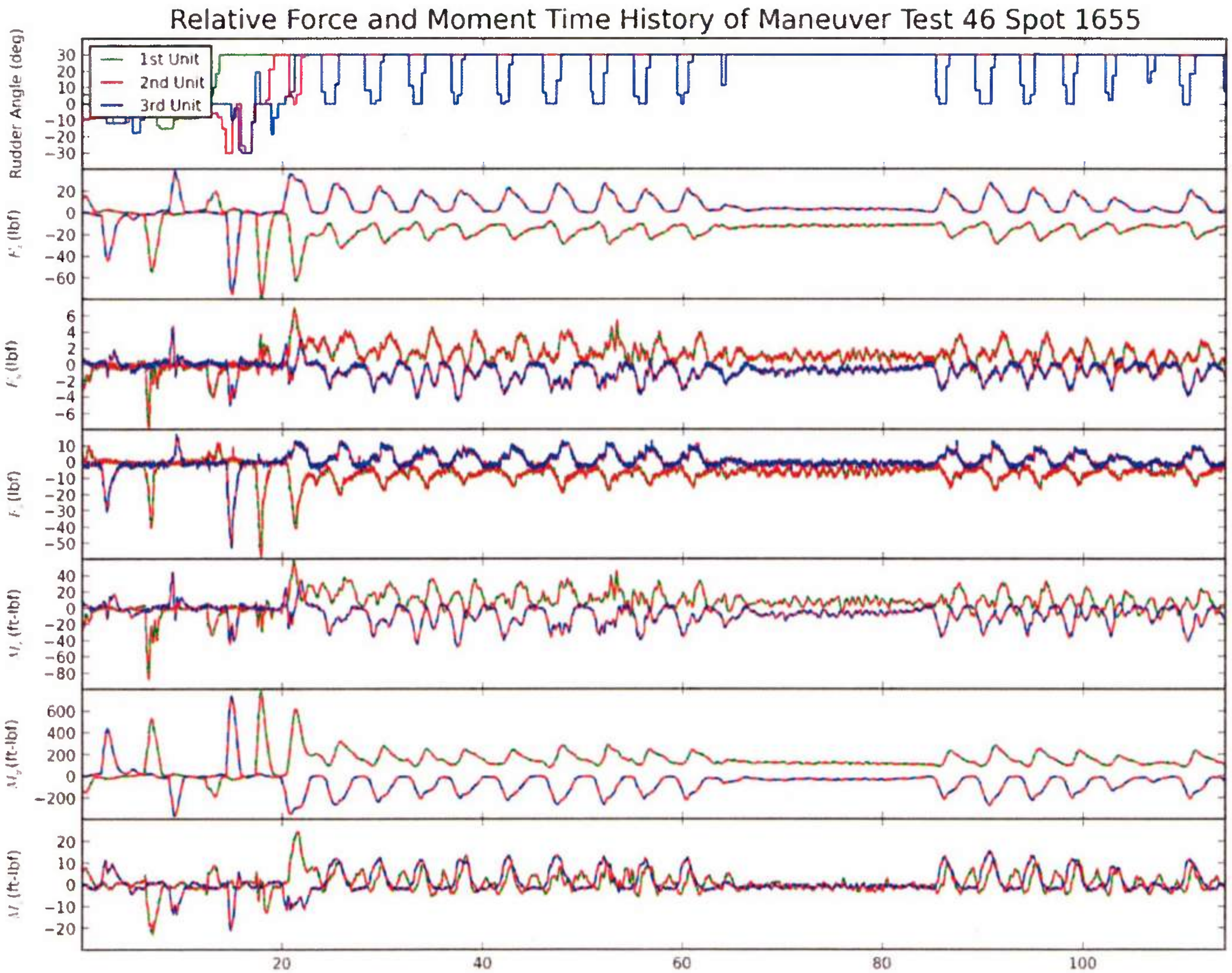



**Figure F-2: Turning circle test , 6 ft/s entry speed, turning diameter 9.1 unit lengths, data**

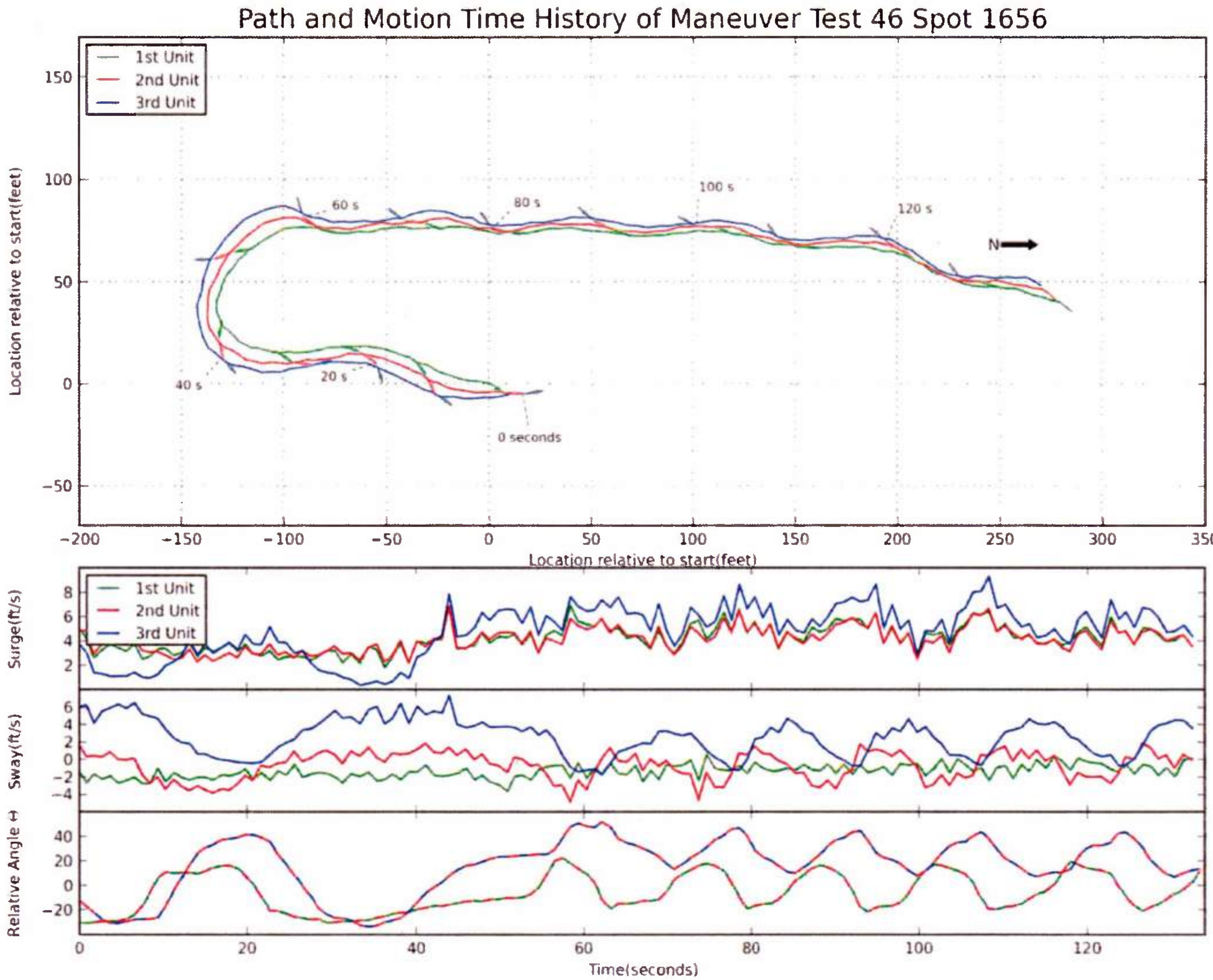



Figure F-3: 180 degree execute, 4 ft/s entry speed, 2-D plot and data

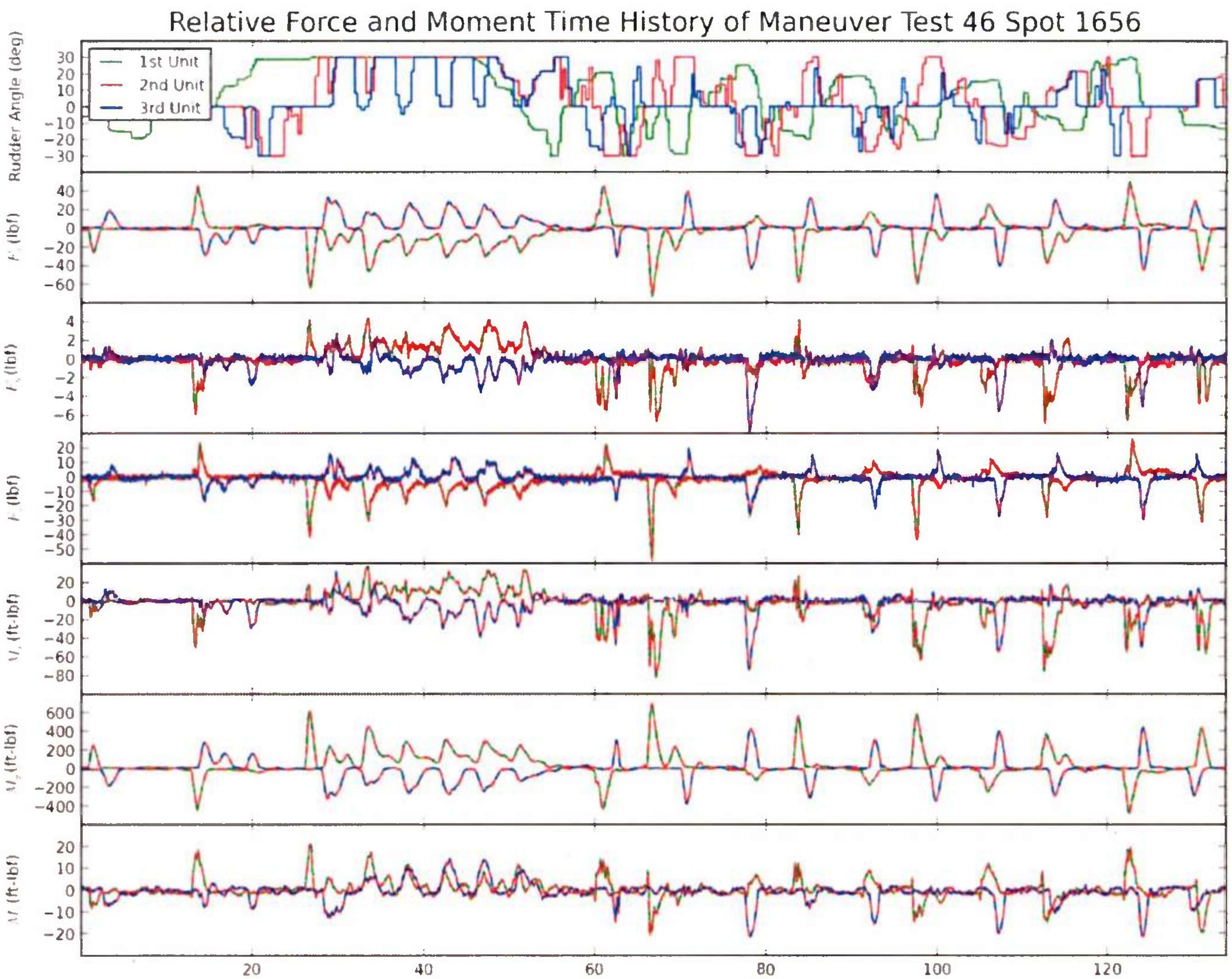



**Figure F-4: 180 degree execute , 4 ft/s entry speed, data**

This page intentionally left blank.

# APPENDIX G: FACILITY DESCRIPTION

## Carriage II - Deep Water Basin

Carriage 2, illustrated in Figure G-1, the deep water basin, is 22 ft deep, 1886 ft long and 51.96 ft wide. A pneumatic wavemaker is located at one end and a wave absorbing beach at the other. The carriage has electro-hydraulic drive and a regenerative braking system with a maximum carriage speed of 20 knots. The pneumatic wavemaker is capable of generating regular waves from 5 to 40 ft in length with corresponding maximum heights of 4 to 24 inches. It can generate irregular waves with a spectrum resembling typical ocean wave patterns with appropriate scale reductions. The wavemaker is divided into two separate equal length sections, each connected to a centrifugal type blower driven by a direct coupled variable speed DC electric motor. The beach on Carriage 2 spans the full width of the basin at the end opposite the wavemaker dome. The absorbing beach is a discontinuous 12 degree slope type made up of 12 permeable layers of rectangular precast concrete bar panels resting on an impermeable concrete slab supported by a structural steel framework. The center section of the beach is of wood construction and can be raised and lowered.

Extending along the length of the basin in both carriages are U-shaped steel wave troughs which act as wave absorbing skimming devices with their upper edges set 0.25 inches below the normal water level surface. The wave troughs dissipate free-surface waves, minimizing the required wait time between runs during calm water testing. For testing in waves the water is lowered approximately 18 inches to a level below the wave troughs to enable unhindered wave generation.

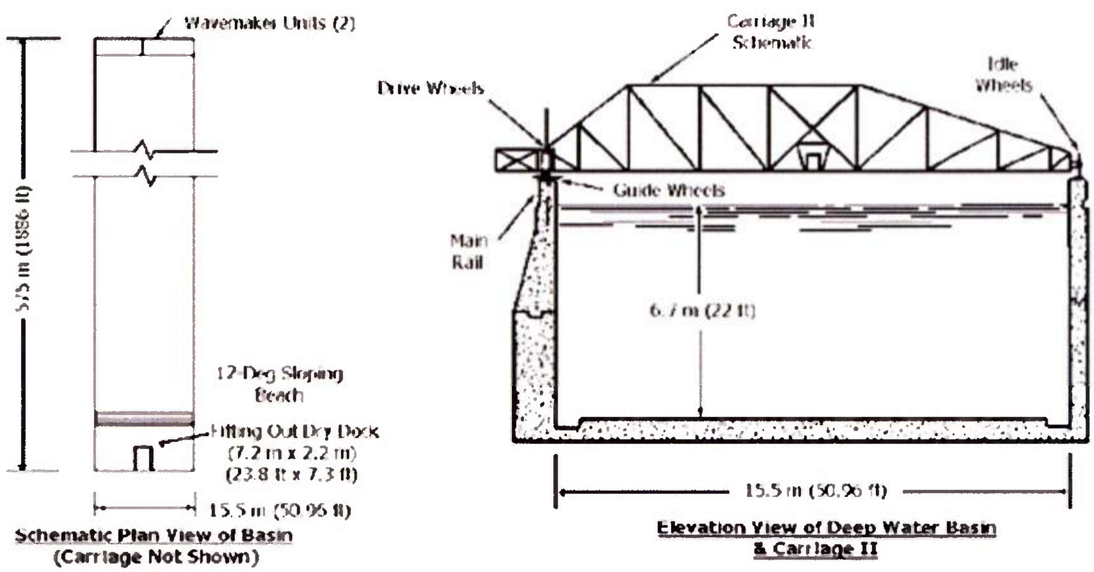



**Figure G-1: DTMB Carriage No. 2 Deep Water Basin drawings**

## Tridelphia Reservoir

The Tridelphia Reservoir is a body of water location in Maryland that has an approximate surface area of 800 acres and depth of 52 feet, which can vary from season to season. Testing can be based on shore and controlled from the shore (Figure G-2) or from small boats.

**Figure G-2: Tridelphia reservoir view from staging docks**

This page intentionally left blank.

# APPENDIX H: MODEL AND INSTRUMENTATION

Body Plan and Side View of Hull

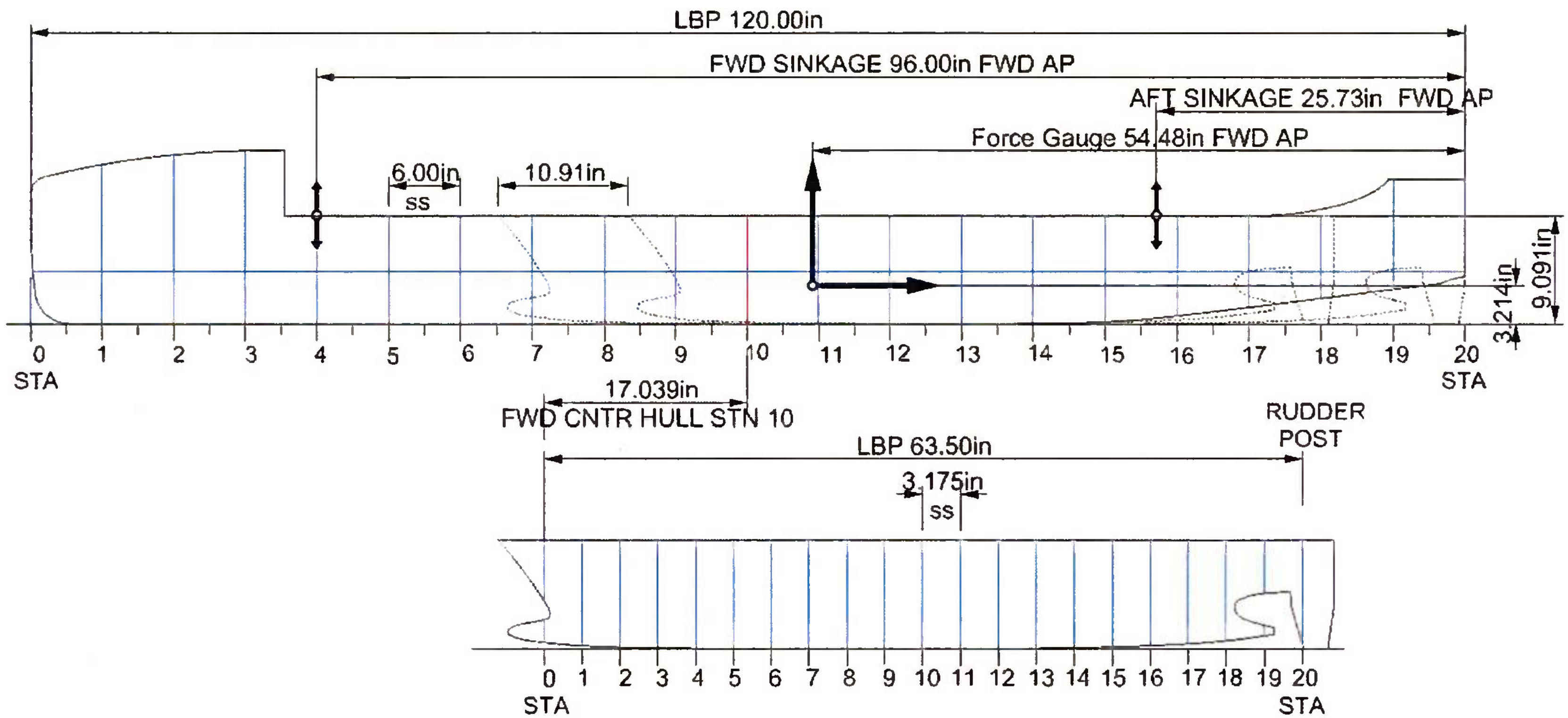



Figure H-1: Model 5714 spacing and layout

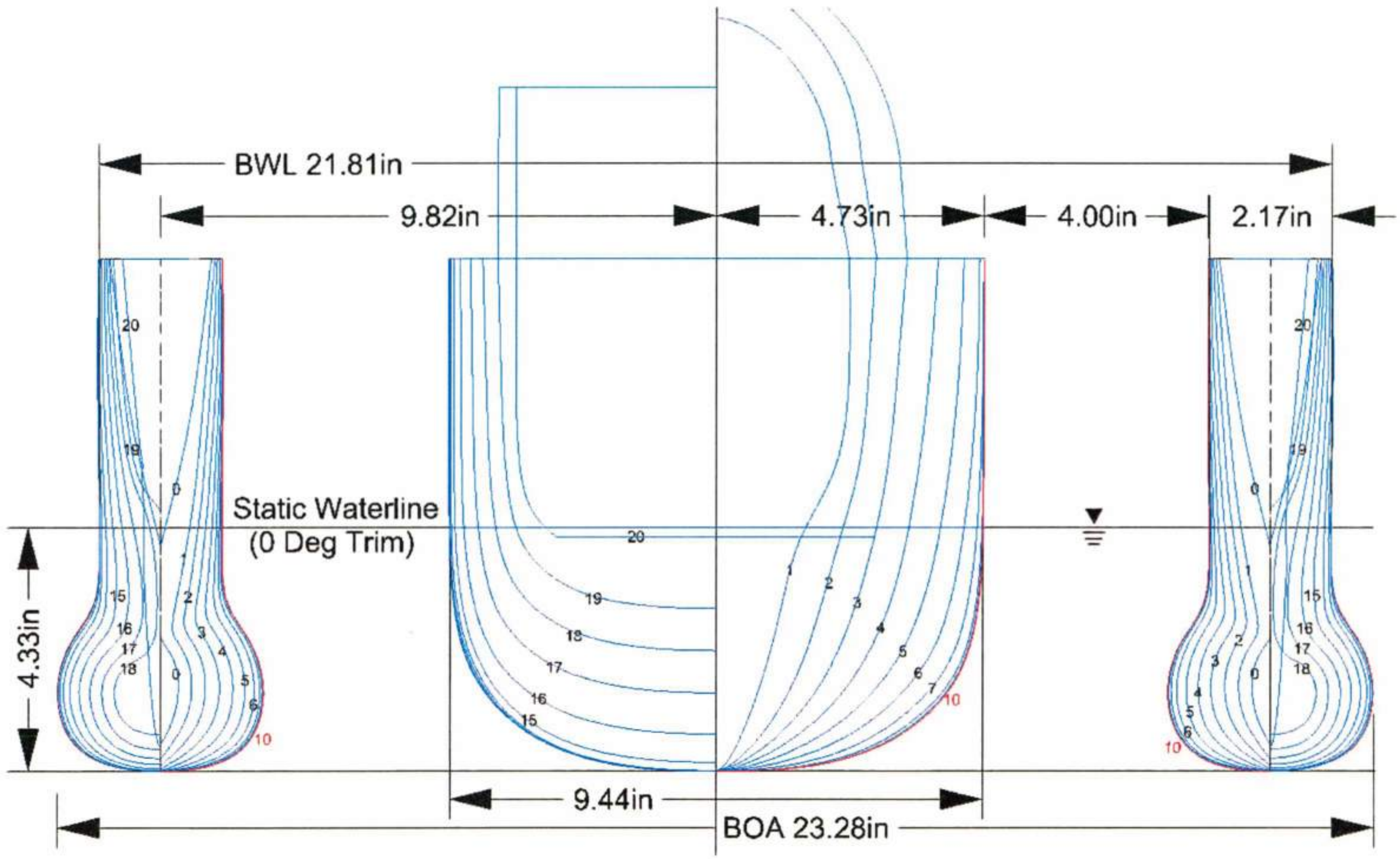



Figure H-2: Model 5714 body plan

## Table H-1: Carriage instrumentation for resistance and wake field

| Channel Name | Measurement | Limits | Sensor Type | Sensor ID # | Cond ID # | Volts | Cal Coefficient Slope Unit/volt | intercept units | Location X Fwd AP | Y Port CL | Z ABL |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **MODEL 1** | | | | | | | | | | | |
| DRAG FORCE | Drag | + 20 lbs | 2-IN BLOCK GAGE - 25 lb | N00167-111006 | | 15v | 9.43686 | 0 | 54.48 | 0 | 3.214 |
| FWD SINKAGE | Fore vertical travel | ± 6 in | STRING POT | N00167-025465 | NI 9239 | 5v | 10.3372 | 0 | 96 | 0 | 9.091 |
| AFT SINKAGE | Aft vertical travel | ± 6 in | STRING POT | N00167-025926 | | 5v | 10.2712 | 0 | 25.726 | 0 | 9.091 |
| **MODEL 2** | | | | | | | | | | | |
| DRAG FORCE | Drag | + 15 lbs | 2-IN BLOCK GAGE - 25 lb | N00167-111007 | | 15v | 9.1523 | 0 | 54.48 | 0 | 3.214 |
| FWD SINKAGE | Fore vertical travel | ± 6 in | STRING POT | N00167-025989 | NI 9239 | 5v | 10.26171 | 0 | 96 | 0 | 9.091 |
| AFT SINKAGE | Aft vertical travel | ± 6 in | STRING POT | N00167-025989 | | 5v | 10.2825 | 0 | 25.726 | 0 | 9.091 |
| **MODEL 3** | | | | | | | | | | | |
| DRAG FORCE | Drag | + 15 lbs | 2-IN BLOCK GAGE - 25 lb | | | 15v | 7.7738 | 0 | 54.48 | 0 | 3.214 |
| FWD SINKAGE | Fore vertical travel | ± 6 in | STRING POT | N00167-025469 | NI 9239 | 5v | 10.2617 | 0 | 96 | 0 | 9.091 |
| AFT SINKAGE | Aft vertical travel | ± 6 in | STRING POT | N00167-025468 | | 5v | 10.2826 | 0 | 25.726 | 0 | 9.091 |
| **MODEL 4** | | | | | | | | | | | |
| DRAG FORCE | Drag | + 15 lbs | 2-IN BLOCK GAGE - 25 lb | N00167-111010 | | 15v | 8.1644 | 0 | 54.48 | 0 | 3.214 |
| FWD SINKAGE | Fore vertical travel | ± 6 in | STRING POT | N00167-025923 | NI 9239 | 5v | 10.2403 | 0 | 96 | 0 | 9.091 |
| AFT SINKAGE | Aft vertical travel | ± 6 in | STRING POT | N00167-025847 | | 5v | 10.4484 | 0 | 25.726 | 0 | 9.091 |
| **VARIOUS** | | | | | | | | | | | |
| MODEL SPEED | Carriage Speed | 10 kts | ENCODER-600 | | counter | | 2 | 0 | | | |
| WAKE RPM | Propeller speed | 1500 rpm | Custom Mag Pickup | | counter | 0 | 15 | 0 | | | |

## Table H-2: Carriage instrumentation for forces and moments

| Channel Name | Measurement | Limits | Sensor Type | Sensor ID # | Cond ID # | Volts | Cal Coefficient Slope Unit/volt | intercept units | Location X Fwd AP | Y Port CL | Z ABL |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **MODEL 2** | | | | | | | | | | | |
| FWD SINKAGE | Fore vertical travel | ± 6 in | STRING POT | N00167-025989 | NI 9239 | 5v | 10.26171 | 0 | 96 | 0 | 9.091 |
| AFT SINKAGE | Aft vertical travel | ± 6 in | STRING POT | N00167-025989 | | 5v | 10.2825 | 0 | 25.726 | 0 | 9.091 |
| FX - UNIT(2) | unit 2 drag | ± 50 lbs | AMTI UW 1.75D | N00167-025985 | | | 287635 | 0 | 54.48 | 0 | 3.214 |
| FY - UNIT(2) | unit 2 lift | ± 50 lbs | AMTI UW 1.75D | N00167-025985 | NI 9237 | 3.3V | 286747.5 | 0 | 54.48 | 0 | 3.214 |
| FZ - UNIT(2) | unit 2 heave | ± 25 lbs | AMTI UW 1.75D | N00167-025985 | | | 1125506 | 0 | 54.48 | 0 | 3.214 |
| MX - UNIT(2) | unit 2 roll moment | ± 100 in-lbs | AMTI UW 1.75D | N00167-025985 | | | 207026.9 | 0 | 54.48 | 0 | 3.214 |
| MY - UNIT(2) | unit 2 pitch moment | ± 100 in-lbs | AMTI UW 1.75D | N00167-025985 | NI 9237 | 3.3V | 209298.3 | 0 | 54.48 | 0 | 3.214 |
| MZ - UNIT(2) | unit 2 yaw moment | ± 100 in-lbs | AMTI UW 1.75D | N00167-025985 | | | 318355.7 | 0 | 54.48 | 0 | 3.214 |
| **MODEL 3** | | | | | | | | | | | |
| FWD SINKAGE | Fore vertical travel | ± 6 in | STRING POT | N00167-025469 | NI 9239 | 5v | 10.2617 | 0 | 96 | 0 | 9.091 |
| AFT SINKAGE | Aft vertical travel | ± 6 in | STRING POT | N00167-025468 | | 5v | 10.2826 | 0 | 25.726 | 0 | 9.091 |
| FX - UNIT(3) | unit 3 drag | ± 5 lbs | AMTI UW 1.75D | N00167-025986 | | | 287583.6 | 0 | 54.48 | 0 | 3.214 |
| FY - UNIT(3) | unit 3 lift | ± 20 lbs | AMTI UW 1.75D | N00167-025986 | NI-9237 | 3.3V | 286456.8 | 0 | 54.48 | 0 | 3.214 |
| FZ - UNIT(3) | unit 3 heave | ± 20 lbs | AMTI UW 1.75D | N00167-025986 | | | 1122989 | 0 | 54.48 | 0 | 3.214 |
| MX - UNIT(3) | unit 3 roll moment | ± 100 in-lbs | AMTI UW 1.75D | N00167-025986 | | | 206608.9 | 0 | 54.48 | 0 | 3.214 |
| MY - UNIT(3) | unit 3 pitch moment | ± 100 in-lbs | AMTI UW 1.75D | N00167-025986 | NI 9237 | 3.3V | 206867.1 | 0 | 54.48 | 0 | 3.214 |
| MZ - UNIT(3) | unit 3 yaw moment | ± 100 in-lbs | AMTI UW 1.75D | N00167-025986 | | | 330161.3 | 0 | 54.48 | 0 | 3.214 |
| **MODEL 4** | | | | | | | | | | | |
| FWD SINKAGE | Fore vertical travel | ± 6 in | STRING POT | N00167-025923 | NI 9239 | 5v | 10.2403 | 0 | 96 | 0 | 9.091 |
| AFT SINKAGE | Aft vertical travel | ± 6 in | STRING POT | N00167-025847 | | 5v | 10.4484 | 0 | 25.726 | 0 | 9.091 |
| FX - UNIT(4) | unit 4 drag | ± 5 lbs | AMTI UW 1.75D | N00167-025987 | | | 291698.9 | 0 | 54.48 | 0 | 3.214 |
| FY - UNIT(4) | unit 4 lift | ± 20 lbs | AMTI UW 1.75D | N00167-025987 | NI 9237 | 3.3V | 310058.5 | 0 | 54.48 | 0 | 3.214 |
| FZ - UNIT(4) | unit 4 heave | ± 20 lbs | AMTI UW 1.75D | N00167-025987 | | | 1135652 | 0 | 54.48 | 0 | 3.214 |
| MX - UNIT(4) | unit 4 roll moment | ± 100 in-lbs | AMTI UW 1.75D | N00167-025987 | | | 219224.2 | 0 | 54.48 | 0 | 3.214 |
| MY - UNIT(4) | unit 4 pitch moment | ± 100 in-lbs | AMTI UW 1.75D | N00167-025987 | NI 9237 | 3.3V | 207623.1 | 0 | 54.48 | 0 | 3.214 |
| MZ - UNIT(4) | unit 4 yaw moment | ± 100 in-lbs | AMTI UW 1.75D | N00167-025987 | | | 337329.8 | 0 | 54.48 | 0 | 3.214 |
| **VARIOUS** | | | | | | | | | | | |
| MODEL SPEED | Carriage Speed | 10 kts | ENCODER-600 | | counter | | 2 | 0 | | | |

## Table H-3: Instrumentation for operational demonstration

| Channel Name | Measurement | Limits | Sensor Type | Sensor ID # | Cond ID # | Volts | Cal Coefficient Slope Unit/volt | Cal Coefficient intercept units | Location X Fwd AP | Location Y Port CL | Location Z ABL |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **MODEL 1** | | | | | | | | | | | |
| MODEL SPEED | speed | 4 kts | GPS CALCULATION | | | | 1 | 0 | 100 | 0 | 14.54 |
| LATITUDE | Fore vertical travel | ± 3 in | GPS | | Serial to Ethernet Switch | | 1 | 0 | 100 | 0 | 14.54 |
| LONGITUDE | Aft vertical travel | ± 3 in | GPS | | Serial to Ethernet Switch | | 1 | 0 | 100 | 0 | 14.54 |
| YAW RATE | Yaw Rate | ± 10 deg/sec | 3dm | | Serial to Ethernet Switch | | 0.000305 | 0 | 96 | 0 | 8.63 |
| HEADING | Heading | 360 deg | 3dm | | Serial to Ethernet Switch | | 0.005493 | 0 | 96 | 0 | 8.63 |
| RUDDER ANGLE | rudder angle | 1500 rpm | STRING POT | | NI 9239 | 5 | 0.000783 | 0 | 13.53 | ± 9.82 | 3.5 |
| SHAFT TORQ | prop torque | + 10 in-lbs | MOTOR CURRENT | | NI 9239 | 0 | 1 | 0 | 15.83 | ± 9.82 | 1.46 |
| SHAFT SPEED | prop rpm | 1500 rpm | ENCODER-600 | | NI 9402 | 15 | 0.1 | 0 | | | |
| **MODEL 1 to 2** | | | | | | | | | | | |
| FX - CONN(1-2) | tension | ± 5 lbs | AMTI UW 1.75D | N00167-025985 | NI 9237 | 3.3V | 287635 | 0 | 114.158 | 0 | 7.5 |
| FY - CONN(1-2) | trans. Shear | ± 20 lbs | AMTI UW 1.75D | N00167-025985 | NI 9237 | 3.3V | 286747.5 | 0 | 114.158 | 0 | 7.5 |
| FZ - CONN(1-2) | vert. Shear | ± 20 lbs | AMTI UW 1.75D | N00167-025985 | NI 9237 | 3.3V | 1125506 | 0 | 114.158 | 0 | 7.5 |
| MX - CONN(1-2) | roll moment | ± 100 in-lbs | AMTI UW 1.75D | N00167-025985 | NI 9237 | 3.3V | 207026.9 | 0 | 114.158 | 0 | 7.5 |
| MY - CONN(1-2) | yaw moment | ± 100 in-lbs | AMTI UW 1.75D | N00167-025985 | NI 9237 | 3.3V | 209298.3 | 0 | 114.158 | 0 | 7.5 |
| MZ - CONN(1-2) | pitch moment | ± 100 in-lbs | AMTI UW 1.75D | N00167-025985 | NI 9237 | 3.3V | 318355.7 | 0 | 114.158 | 0 | 7.5 |
| **MODEL 2** | | | | | | | | | | | |
| YAW RATE | Yaw Rate | ± 10 deg/sec | 3DM | | Serial to Ethernet Switch | | 0.000305 | 0 | 96 | 0 | 8.63 |
| HEADING | Heading | 360 deg | 3DM | | Serial to Ethernet Switch | | 0.005493 | 4.195459 | 96 | 0 | 8.63 |
| RUDDER ANGLE | rudder angle | ± 30 deg | STRING POT | | NI 9239 | 5 | 0.000783 | 0 | 13.53 | ± 9.82 | 3.5 |
| SHAFT TORQ | prop torque | + 10 in-lbs | MOTOR CURRENT | | NI 9239 | 0 | 1 | 0 | 15.83 | ± 9.82 | 1.46 |
| SHAFT SPEED | prop rpm | 1500 rpm | ENCODER-600 | | NI 9402 | 15 | 0.1 | 0 | | | |
| **MODEL 2 to 3** | | | | | | | | | | | |
| FX - CONN(2-3) | tension | ± 5 lbs | AMTI UW 1.75D | N00167-025986 | NI 9237 | 3.3V | 287583.6 | 0 | 114.158 | 0 | 7.5 |
| FY - CONN(2-3) | trans. Shear | ± 20 lbs | AMTI UW 1.75D | N00167-025986 | NI 9237 | 3.3V | 286456.8 | 0 | 114.158 | 0 | 7.5 |
| FZ - CONN(2-3) | vert. Shear | ± 20 lbs | AMTI UW 1.75D | N00167-025986 | NI 9237 | 3.3V | 1122989 | 0 | 114.158 | 0 | 7.5 |
| MX - CONN(2-3) | roll moment | ± 100 in-lbs | AMTI UW 1.75D | N00167-025986 | NI 9237 | 3.3V | 206608.9 | 0 | 114.158 | 0 | 7.5 |
| MY - CONN(2-3) | yaw moment | ± 100 in-lbs | AMTI UW 1.75D | N00167-025986 | NI 9237 | 3.3V | 206867.1 | 0 | 114.158 | 0 | 7.5 |
| MZ - CONN(2-3) | pitch moment | ± 100 in-lbs | AMTI UW 1.75D | N00167-025986 | NI 9237 | 3.3V | 330161.3 | 0 | 114.158 | 0 | 7.5 |
| **MODEL 3** | | | | | | | | | | | |
| YAW RATE | Yaw Rate | ± 10 deg/sec | 3DM | | Serial to Ethernet Switch | | 0.000305 | 0 | 96 | 0 | 8.63 |
| HEADING | Heading | 360 deg | 3DM | | Serial to Ethernet Switch | | 0.005493 | -13.5553 | 96 | 0 | 8.63 |
| RUDDER ANGLE | rudder angle | 1500 rpm | STRING POT | | NI 9239 | 5 | 0.1 | 0 | 13.53 | ± 9.82 | 3.5 |
| SHAFT TORQ | prop torque | + 10 in-lbs | MOTOR CURRENT | | NI 9239 | 0 | 0.00783 | 0 | 15.83 | ± 9.82 | 1.46 |
| SHAFT SPEED | prop rpm | 1500 rpm | ENCODER-600 | | NI 9402 | 15 | 0.1 | 0 | | | |

## AMTI 6-Component balances interaction matrices

### Table H-4: AMTI 1.75D, N00167-025985, model 2 interaction matrix

| Input Force/Moment | Resultant Force/Moment: Fx | Fy | Fz | Mx | My | Mz |
|---|---|---|---|---|---|---|
| Fx | 1.000420848 | -0.018461688 | -0.021054662 | 0.032575416 | -0.027192041 | -0.00606253 |
| Fy | 0.016787924 | 0.999916831 | 0.006624249 | 0.012514307 | 0.012665773 | 0.004272452 |
| Fz | -0.022267907 | 0.017349452 | 0.990430211 | 0.077615471 | 0.193943782 | -0.01736326 |
| Mx | 0.00505152 | -0.000759981 | -0.041549994 | 0.998447421 | -0.004197371 | -0.00103004 |
| My | 0.000623533 | 0.003453585 | -0.034616822 | -0.01889941 | 0.994111767 | -0.00083156 |
| Mz | 0.000126087 | 0.000412468 | 0.001423911 | 0.00399053 | 0.001661152 | 0.999990623 |

### Table H-5: AMTI 1.75D, N00167-025986, model 3 interaction matrix

| Input Force/Moment | Resultant Force/Moment: Fx | Fy | Fz | Mx | My | Mz |
|---|---|---|---|---|---|---|
| Fx | 1.000055737 | 0.008601553 | 0.008322938 | -0.003501714 | -0.018878837 | -0.01795817 |
| Fy | 0.029048116 | 1.000131229 | -0.019757777 | 0.083307473 | 0.079767365 | -0.03566032 |
| Fz | -0.023265761 | -0.017150292 | 0.99668103 | -0.057124908 | 0.145861319 | 0.00708198 |
| Mx | 0.007234455 | -0.001175559 | -0.043998256 | 1.002643264 | -0.004313123 | -0.00659475 |
| My | 0.002441023 | -0.002495598 | -0.040391806 | -0.004416378 | 0.994268505 | -0.00831147 |
| Mz | -0.002206134 | 0.002820741 | 0.006915497 | -0.000886216 | -0.002949215 | 1.000817139 |

### Table H-6: AMTI 1.75D, N00167-025987, model 4 interaction matrix

| Input Force/Moment | Resultant Force/Moment: Fx | Fy | Fz | Mx | My | Mz |
|---|---|---|---|---|---|---|
| Fx | 1.000420848 | -0.018461688 | -0.021054662 | 0.032575416 | -0.027192041 | -0.00606253 |
| Fy | 0.016787924 | 0.999916831 | 0.006624249 | 0.012514307 | 0.012665773 | 0.004272452 |
| Fz | -0.022267907 | 0.017349452 | 0.990430211 | 0.077615471 | 0.193943782 | -0.01736326 |
| Mx | 0.00505152 | -0.000759981 | -0.041549994 | 0.998447421 | -0.004197371 | -0.00103004 |
| My | 0.000623533 | 0.003453585 | -0.034616822 | -0.01889941 | 0.994111767 | -0.00083156 |
| Mz | 0.000126087 | 0.000412468 | 0.001423911 | 0.00399053 | 0.001661152 | 0.999990623 |

INITIAL REPORT DISTRIBUTION

| Print | PDF | |
|---|---|---|
| 1 | 1 | NAVSEA, PEO SHIPS PMS385 D. Liese |
| 1 | 1 | PEO SHIPS PMS 385 S. Clark |
| 1 | 1 | SEA 05, J. Webster |
| 1 | 1 | SEA 05, P. Alman |
| 1 | 1 | SEA 05D1, J. Slutsky |
| 1 | | CSC, I. Mizine<br>1201 M Street SE, Suite 400<br>Washington DC 20003 |
| 1 | | DTIC |

Internal Distribution

| Print | PDF | |
|---|---|---|
| | 1 | 3452 Library |
| | 1 | 801 T. Fu |
| 1 | 1 | 8130 A. Rausch |
| | 1 | 82 J. Hough |
| | 1 | 8202 C. Dorger |
| | 1 | C. Kennel |
| 1 | 1 | 85 G. Karafiath |
| | 1 | J. Brown |
| 2 | 1 | Office Files |
| | 1 | 851 T. Smith |
| | 1 | 852 D. Hayden |
| | 1 | 853 R. Waters |
| | 1 | 854 M. Donnelly |
| | 1 | B. Metcalf |
| | 1 | E. Giesberg |
| | 1 | 873 S. Black |